GAS PHASE CYCLISATION REACTIONS OF AROMATIC FREE RADICALS

by

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Lecture Courses

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"Approaches to Synthesis"

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Professor K.R. Jennings (University of Warwick)

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"Introduction to Management"

Department of Business Studies (University of Edinburgh)

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A B S T R A C T

A range of *o*-substituted phenoxyl and thiophenoxyl radicals, derived from aryl salicylates, were generated by flash vacuum pyrolysis (F.V.P.) of the corresponding allyl ether at 650°C, or iso-propyl ether at 750°C, as appropriate.

These species can subsequently undergo intramolecular cyclisation reactions and therefore, by careful precursor design, a series of fused heterocyclic systems can be prepared. Thus routes to 7-hydroxyphthalides, 7-hydroxy-isoindolones, and benzofurans are described, together with an efficient synthesis of dibenzofurans and dibenzothiophenes which involves a novel rearrangement-extrusion-cyclisation pathway.

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EXPERIMENTAL

INTRODUCTION

P R E A M B L E

Until recently, the use of free radicals in organic synthesis, has been limited mainly due to their lack of selectivity. However, in recent years many "well-designed" high-yielding radical reactions have been developed[1,2]. This review aims to outline the currently available practical methods which are used to effect intramolecular cyclisation in both the condensed and vapour phase. The regiospecificity of bond formation of these reactions in solution is described with reference to the guidelines laid down by Beckwith *et al*[3]. The application of reactions, in both phases, to the formation of hetero-cycles is considered with respect to ring size, and the influence, if any, of the heteroatom(s) involved. Examples will be cited which concern both carbon-carbon and carbon-heteroatom bond formation.

However, this review does not attempt to present an exhaustive survey of synthetic radical cyclisations, nor does it attempt to discuss the mechanistic details in any depth. The subject has been thoroughly reviewed in numerous publications[1,2], which also include those of Ramaiah[4], Hart[5], and Walling[6].

I CONDENSED PHASE CYCLISATIONS

The majority of free radical reactions in solution, which are of interest to the synthetic organic chemist, are chain processes and involve three major steps: (1) radical initiation; (2) chain propagation (by electron, group, or atom transfer); and (3) termination. The successful execution of the radical sequences requires the selective reaction of intermediate radicals in the presence of several potentially reactive components. Substituent effects can often provide this control element. The methods used to conduct such chain processes require that the radicals are generated in a site-selective manner, and that they have sufficient time to react before decomposing by chain termination. Chain rate constants are well-documented[7] and therefore many reactions can be planned.

Initiation can be achieved directly using thermal activation and in some cases an initiator is employed, usually azobisisobutyronitrile (AIBN). Photo-initiation or redox-initiation can be employed for reactions carried out at low temperatures.

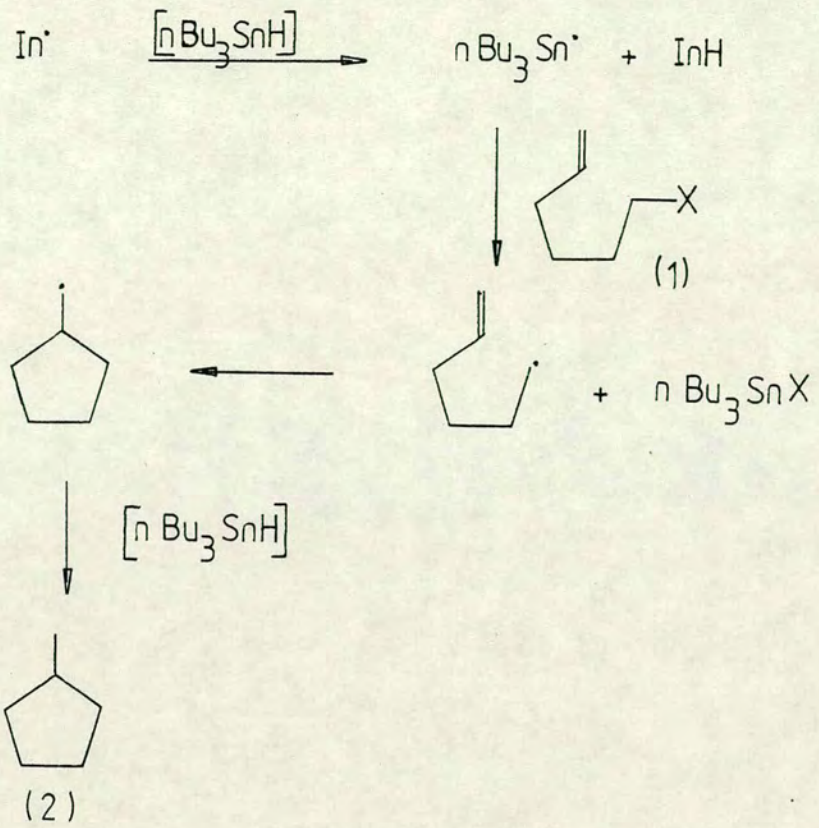
A. Chain methods for radical propagation in carbon-carbon bond formation

Despite the vast range of radical carbon-carbon bond forming reactions, only a relatively few practical methods are available: these are (1) the tin-hydride method; (2) the fragmentation method; (3) the thiohydroxamate

method; (4) the "Atom Transfer" method; and (5) the well-established Pschorr-reaction, used for effecting internuclear cyclisations exclusively.

(i) The tin hydride method

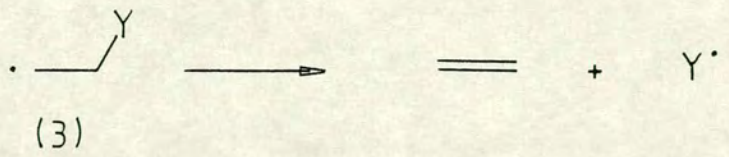
Currently, this is the most commonly used method for carbon-carbon bond formation in radical reactions[8]. Its mode of action involves the generation of a chain carrier $Bu_3Sn^{\cdot}$ from tributyltin hydride (TBTH) using AIBN. The propagation sequence begins with atom or group (X) abstraction from the precursor (1); X can be I, Br, SePh, SPh and secondary xanthate esters. Hence the site of the initial radical is determined by the location of (X). The species can then cyclise intramolecularly, and the product (2) is reduced relative to the precursor (Scheme 1). This reaction is discussed in more detail in Section IB1.



SCHEME 1

(ii) The fragmentation method

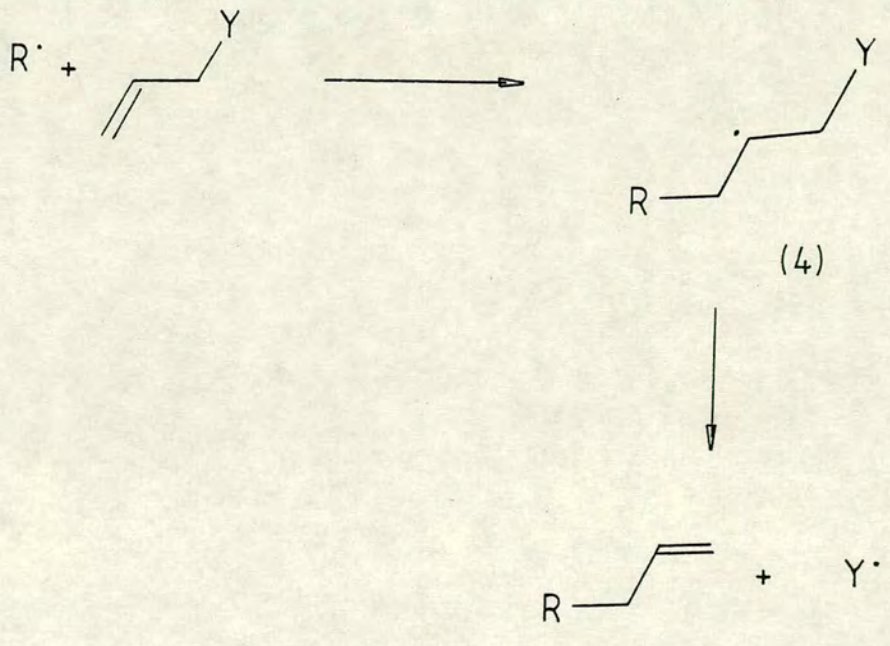
In this case, the chain transfer agent (eg $Bu_3Sn^{\cdot}$) is generated by a fragmentation (rather than a hydrogen atom abstraction) reaction. The rapid fragmentation of an appropriate C-Y bond in (3) producing $Y^{\cdot}$, which acts as the chain transfer agent in intramolecular cyclisations (Scheme 2); Y can be trialkyltin, cobaloxime[9] or thiophenyl.



(3)

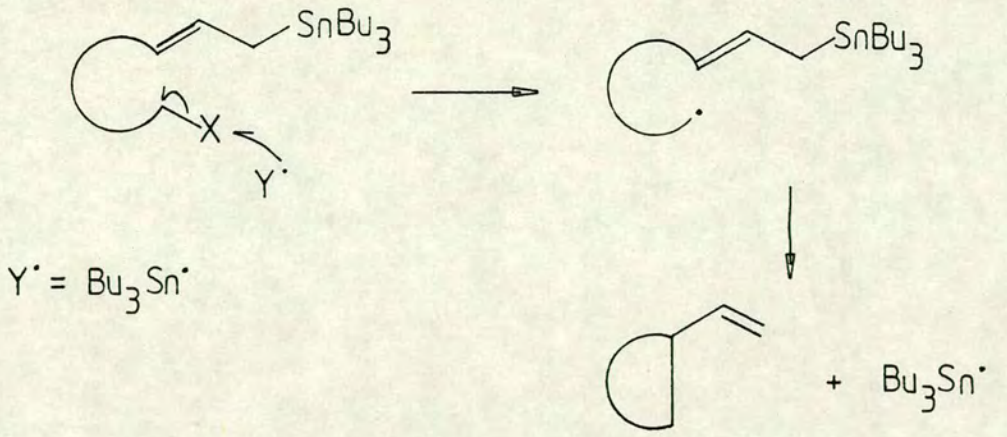
SCHEME 2

Intermediates related to (3) are commonly generated by addition to an appropriately substituted allyl derivative (Scheme 3), thus resulting in overall allylation of a suitable radical precursor. Intermolecular cyclisation may proceed as in Scheme 4.



(4)

SCHEME 3

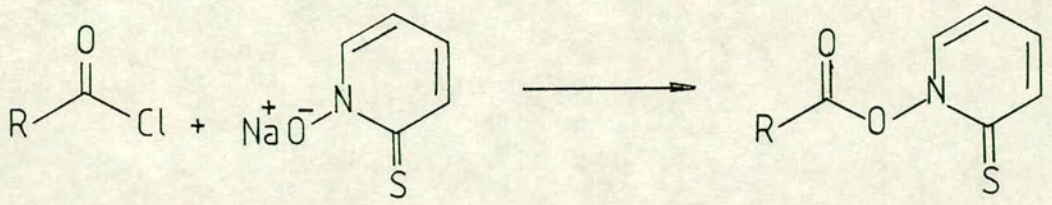


SCHEME 4

Although the chain transfer agent can be the same as in the tinhydride method ($Bu_3Sn^{\cdot}$) and initial radicals are generated by the same abstraction step, this method is advantageous in that no tinhydride is present, so intermediate radicals are not intercepted by hydrogen atom abstraction. Secondly, few reactions can be expected to compete with the rapid fragmentation of (4), thus permitting long lifetimes for intermediate radicals which enables relatively slow reactions to take place.

(iii) The thiohydroxamate ester method

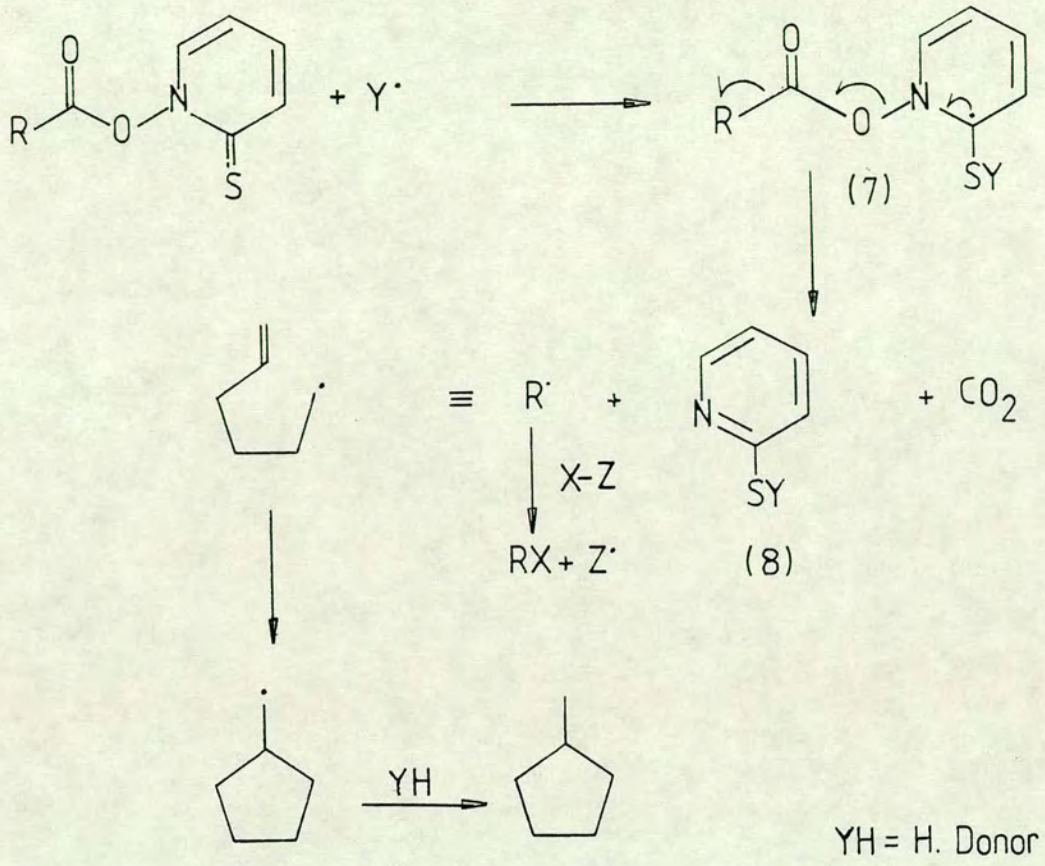
Developed by Barton[10], the thiohydroxamic esters (6) are readily prepared from the appropriate acid chloride and the sodium salt of the pyridinethione (5) (Scheme 5).



(5) (6)

SCHEME 5

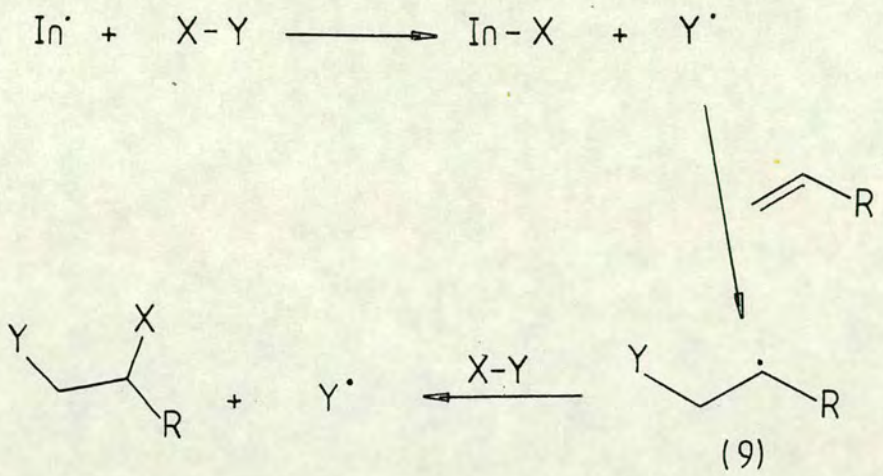
Barton[11] has suggested a possible propagation sequence, illustrated in Scheme 6. This involves addition of the alkyl radical Y$^{\bullet}$ to the thiohydroxamate producing (7). Fragmentation of (7) produces CO_2, the pyridine thioether (8) and the radical R$^{\bullet}$ which can cyclise intramolecularly or be intercepted by a variety of neutral molecules[12](X-Z).



SCHEME 6

(iv) The "Atom-transfer" method

The addition of a reagent X-Y across a carbon-carbon double (or triple) bond is a fundamental reaction of organic free radicals[13]. X can be hydrogen or halogen, and Y can be carbon or heteroatom. The transformation is often referred to as a Kharasch addition (Scheme 7).



SCHEME 7

The radical that undergoes addition (Y·) is generated directly by atom abstraction from the starting material X-Y. Unlike the tinhydride method, both chain transfer and site-selective generation of the initial radical are combined in a single step. An atom-transfer-mediated reaction has two basic requirements: (1) a rapid exothermic addition (or cyclisation) reaction must convert the relatively stable radical (Y·) to the less stable (9), and (2) the atom donor (X-Y) must be able to transfer X more rapidly than other competing reactions of (9) such as radical termination or polymerisation. Pattenden[14] has reported an extension to this method using Cobalt(III) complexes.

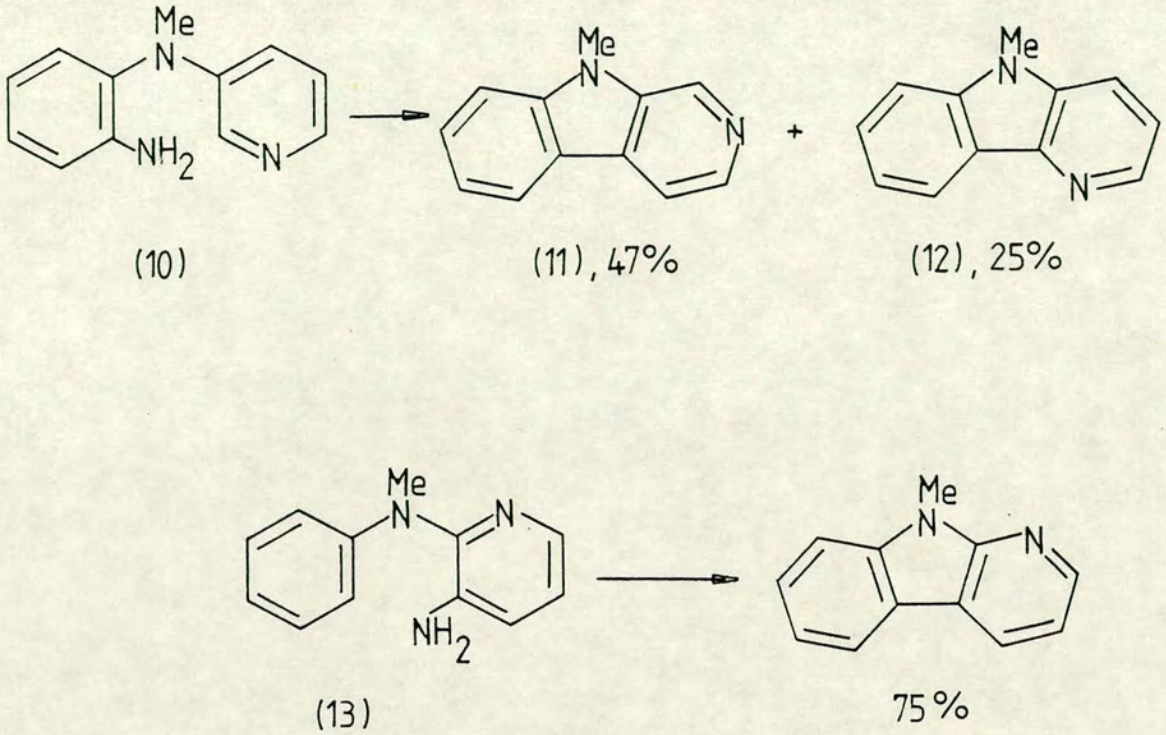
(v) The Pschorr reaction

First reported in the last century, this was originally

applied to the preparation of phenanthrene derivatives[15] from aryldiazonium salts. The reaction is limited to internuclear cyclisations (Scheme 8) and may proceed either homolytically[16] or heterolytically[17] depending on the conditions employed. Acid-catalysed procedures effect an electrophilic substitution, whereas in the presence of a reducing agent such as Cu° or iodide[18], a phenyl σ radical can be produced.

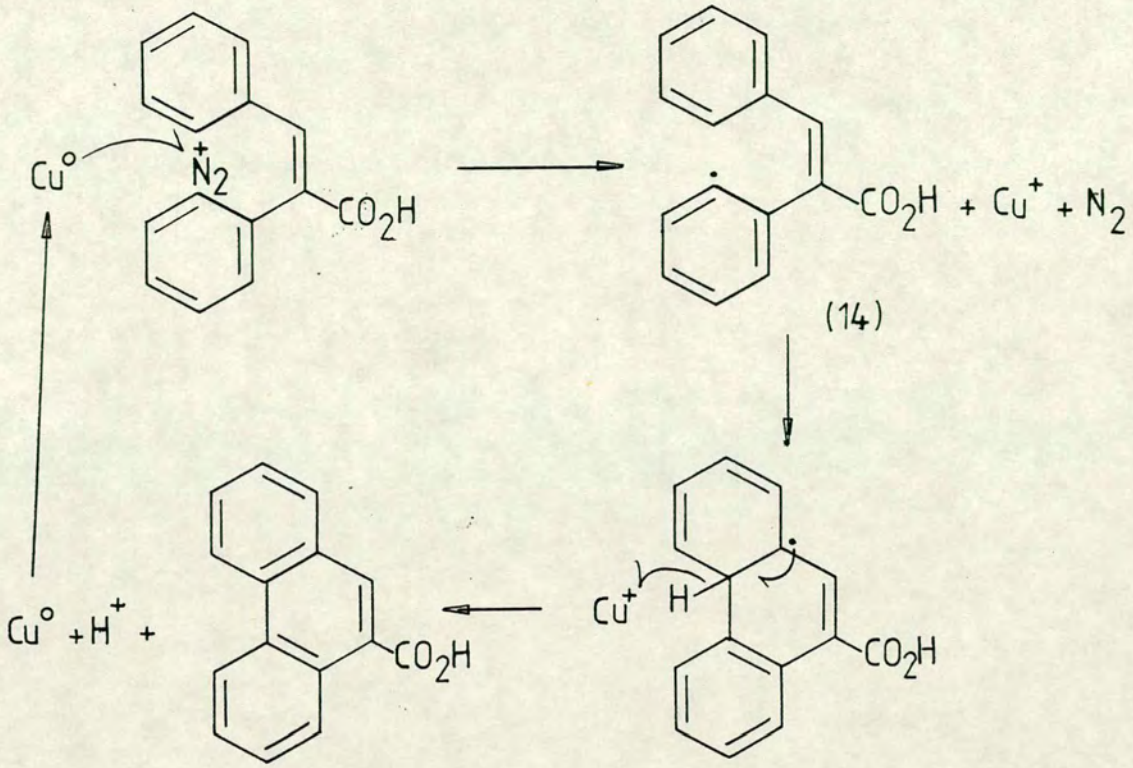
SCHEME 8

The homolytic mechanism is supported by evidence depicted in Scheme 9[16]. It was found that the diazonium sulphate from the pyridylaniline (10) was cyclised with copper powder to a mixture of carbolines (11) and (12), in approximately the same total yield as the corresponding cyclisation of the anilinoaminopyridine (13). However, under the mild conditions employed, electrophilic substitution on the deactivated pyridine ring should proceed less readily than on the benzenoid ring. This is not the case with radical substitutions. Moreover the yield of (11) is greater than that of (12), indicating that 2-substitution predominates over 4-substitution, as in other radical reactions on pyridine.



SCHEME 9

The Cu°-promoted homolytic reaction may proceed via a one-electron transfer[19] as shown in Scheme 10. This is a chain reaction because Cu° is returned to the system after each cycle.



SCHEME 10

The reaction is limited by structural requirements as (1) the carbon atoms that are to be linked should be between 1.5Å and 2.5Å apart[20], and (2) where geometrical isomers can exist as in (14), only the E isomer can cyclise in this manner.

B. Intramolecular cyclisations

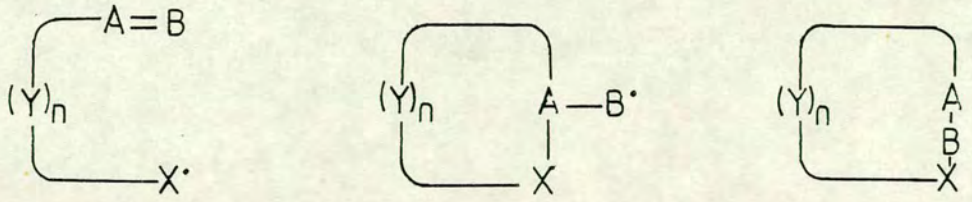
Radical intramolecular cyclisations of alkenyl radicals have been applied to the synthesis of carbocyclic and heterocyclic systems, and can be carried out with C-C, C-O and C-N multiple bonds as radical traps. These reactions can exhibit interesting regioselectivities and stereoselectivities which can differ from the corresponding

cationic processes, thus permitting alternative preferential ring formations. Generally five- and six-membered rings can be formed at rates fast enough for a successful application to synthesis, but neither three- nor four-membered rings can be synthesised because the rate of ring opening exceeds that of ring closure[2]. The stereochemical selectivities of these reactions are discussed in principle and in relation to their synthetic applications. However these generalisations do not apply to the Pschorr reaction, and this will be discussed separately (Section IB4).

1 Regioselectivity

Cationic cyclisations tend to favour six-membered ring formation, whereas kinetically-controlled radical initiated cyclisations, in corresponding systems, usually lead to a predominance of the five-membered ring products. Beckwith[21] has derived a series of guidelines, which can predict the stereochemical outcome of kinetically-controlled cyclisations of simple 5-hexenyl radicals. The following two generalisations concern regioselectivity.

(1) "In lower alkenyl, alkynyl and related radicals, intramolecular additions occur preferentially in the *exo*-mode". This is shown in Scheme 11, where *exo*-ring closure (15)→(16) is kinetically favoured over the *endo* process (15)→(17) for radicals of type (15), where Y represents a chain of atoms ($n \leqslant 5$).



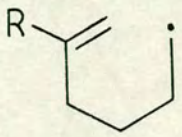
(15) (16) (17)

SCHEME 11

This guideline is exemplified by ring closure of butenyl[22], hexenyl, heptenyl and octenyl radicals[23], and of oxygen[24] and nitrogen-centred[25] radicals. It appears to apply to ring closure onto C≡N[26], C=O and aromatic nucleii[27], but does not apply to systems under thermodynamic control, nor to some 5-substituted hex-5-enyl radicals (see ii). In this case the thermodynamically more stable *endo*-product is disfavoured because of the highly strained transition state required for its formation[28].

(ii) "Substituents on an olefinic bond disfavour homolytic addition at the substituted position"

Thus 5-substituted hex-5-enyl radicals (18) and (19) undergo mainly 6-membered ring formation because the rate of 1,5-cyclisation is retarded due to steric effects.



(18 ; R = Me)
(19 ; R = ^{i}Pr)

Systems containing a silicon atom[29] or an amido[30] group in the chain can also favour 6-membered ring formation, although substituents at the radical centre have little effect[23].

2. Stereoselectivity

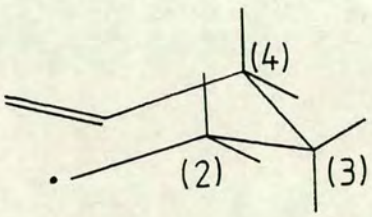
Beckwith formulated that:-

(i) 1- or 3-substituted radicals preferentially give *cis* disubstituted cyclopentyl products, and 2- or 4-substituted radicals give mainly the *trans* product. However, radical additions to cyclic alkenes result in mainly *cis* products, due to strain effects[3].

These rules can be explained by the transition state structure (20) in which axial and equatorial positions are distinguishable at C-2, C-3 and C-4. Thus, the more favoured conformer should contain the substituents in the equatorial position.

Bulky substituents at C-2, C-3 and C-4 can accentuate these effects, however when large groups are present at C-1 the guideline may fail[31].

Exceptions to these guidelines can also occur where:
(i) An oxygen or nitrogen atom replaces C-3, in the alkyl chain (21) and (22). In this case generally 5-*exo*



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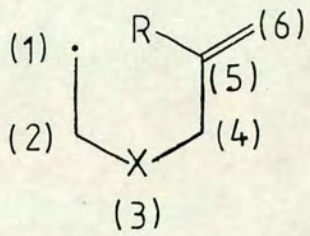
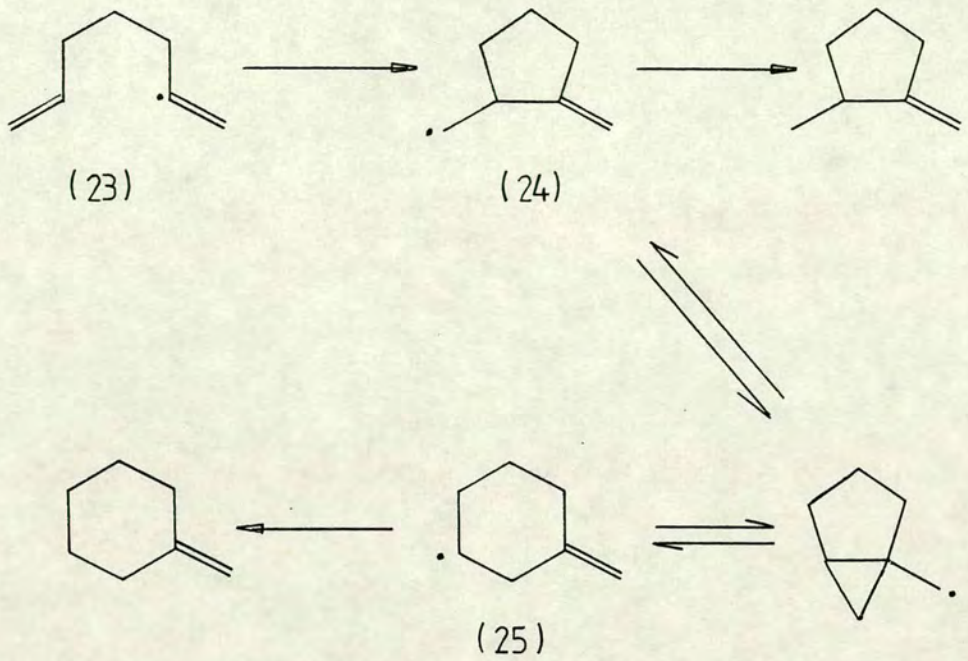


(21; X = O)
(22; X = NH)

cyclisations predominate, even when C-5 has a bulky substituent. This arises because the C-X bond, being shorter than the corresponding C-C bond, reduces the distance between C-1 and C-5 and therefore promotes attack at this position. And where:
(ii) Aryl or vinyl (23) radicals are generated (with (TBTH at low concentrations), 6-*endo* cyclisation is favoured[32] (Scheme 12). Stork[32] has suggested that this occurs because the homoallylic nature of the initially formed radical (24) enables it to embark on a rearrangement pathway, which, at the hydrogen donor concentrations, is under thermodynamic control. Therefore the more stable radical (25) (a secondary radical) is formed predominantly.



SCHEME 12

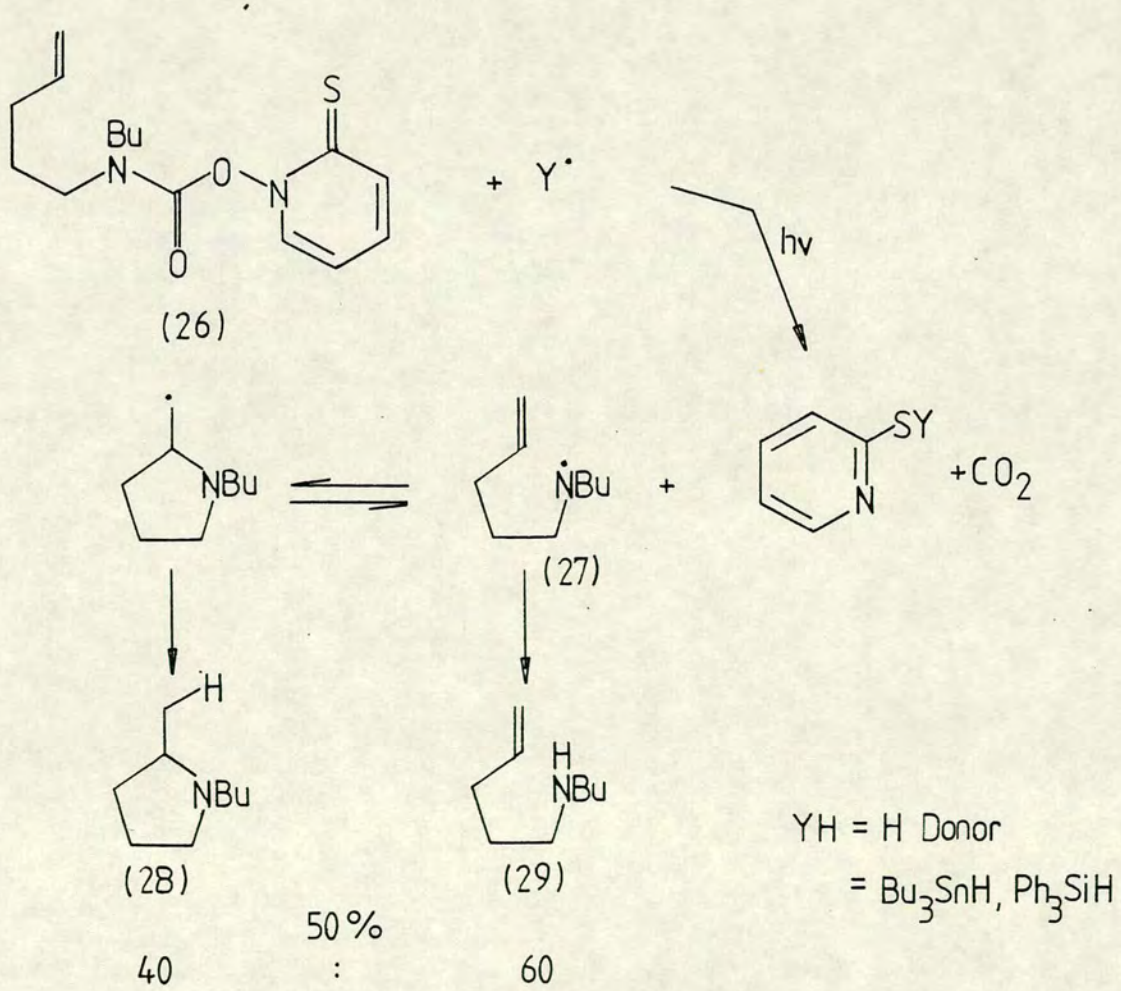
3. Some synthetic heterocyclisations

The synthetic applications of these reactions have been detailed comprehensively in several reviews[1,2,4], however this survey aims to illustrate the general points discussed above by highlighting only a few recent examples of 5- and 6-membered heterocycle formation. The cyclisations considered are each mediated by one of the general methods described in Section IA(i)-(iv), and thus can involve either carbon-carbon or carbon-heteroatom bond formation. Internuclear cyclisations mediated by the Pschorr reaction are discussed in Section IB4.

(i) Five-membered rings

In hex-5-enyl carbon-centred radicals the predominance

of *exo* cyclisation over 5-*endo* closure has tremendous synthetic importance[1], however this preference can also be shown by aminyl radicals (27), generated by the thiohydroxamate ester method. In this case, shown in Scheme 13, the precursor (26) reacts with a silicon or tin-centred radical (Y·) liberating the aminyl (27) which can cyclise, apparently reversibly, in the 5-*exo*-mode exclusively to form pyrrolidine (28) or produce the acyclic product (29) by a hydrogen abstraction[33]. Moderate yields of the pyrrolidine can be obtained, although the acyclic product is generally favoured.



SCHEME 13

Substitution at C-5 generally promotes 6-*endo* cyclisation, however replacement of C-3 in the alkyl chain, with a smaller oxygen or nitrogen atom can favour reaction at C-5. One such example involves the TBTH-mediated conversion of 2-bromoethyl allyl sulphonamides (30) to pyrrolidine (31) in high yield[34] (Scheme 14). Similarly, in related oxygen-substituted systems[35,36],

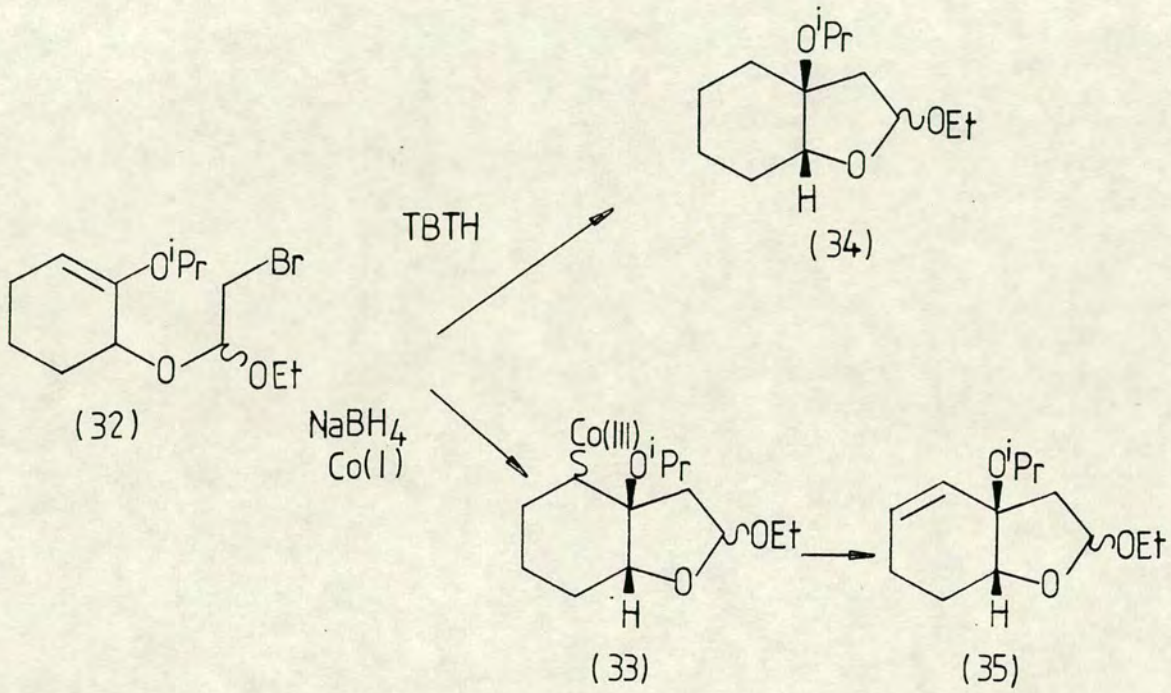
(30) (31)

R=H ; 87%
R=Me ; 85%

SCHEME 14

precursors to γ-lactones (34) and (35) have been obtained in high yield from the 5-substituted vinyl ether bromo acetal (32) by using both a tinhydride and a Co(I)-mediated reaction, respectively[37] (Scheme 15). However, it is notable that the anticipated reduced product (34) is obtained with TBTH, whereas the alkene (35) formed in the presence of the Co(I) reagent may result from a 1,2-elimination of Co-H from the intermediate cobaloximato (33)

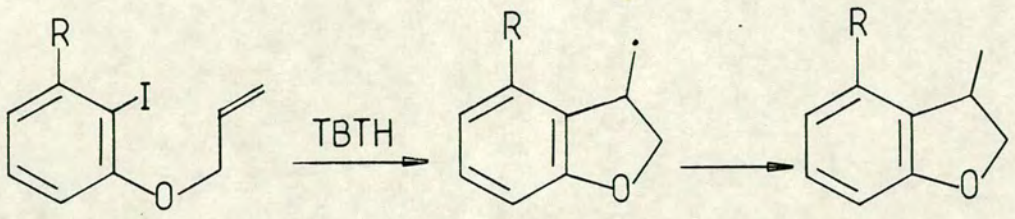
species produced in the initial radical cyclisation[37]. In both cases, the *cis*-isomer is obtained as is expected for radical cyclisation onto a cyclic alkene (Section IB2) and also in view of the considerable ring strain inherent in the corresponding *trans* fused products[37].



SCHEME 15

These reactions can be extended to aryl radicals, which are very reactive toward cyclisation[1,38]. Indeed, aryl iodides of type (36) can undergo reductive cyclisation with TBTH to give dihydrobenzofurans (38) in high yield[38] (Scheme 16). Although the homoallylic nature of the initially formed radical (37) should promote 6-*endo* cyclisation, the 5-*exo* process is accelerated because of

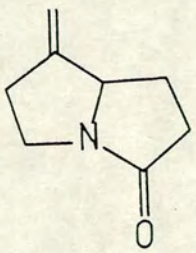
the oxygen atom and thus the kinetically favoured product is obtained exclusively.



(36) (37) (38)

SCHEME 16

Radical cyclisations have also been applied to the synthesis of fused heterocycles, such as pyrrolizidinones[39] (39) and carbacephams[40] (40).



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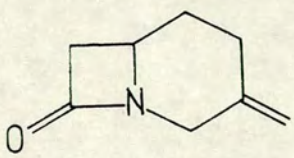
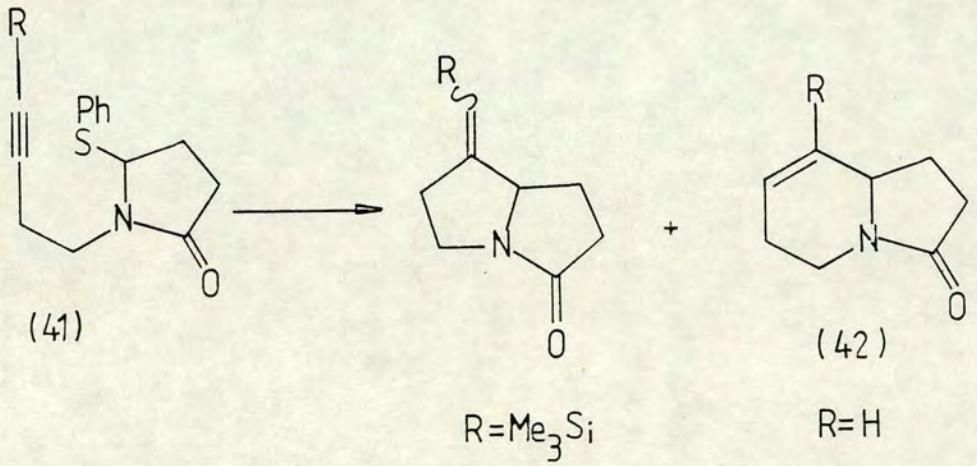


(40)

Pyrrolizidinones have been synthesised by Hart[39], the process involving the TBTH-mediated generation and cyclisation of stabilised α-acylamino radicals from

phenyl thiolactams (41) (Scheme 17). Often yields are low because the presence of the amide group in the connecting chain reduces the rate of 5-*exo* cyclisation and leads to 6-*endo* product formation (ie indolizidinone, 42). This effect may be related to the geometric constraints imposed by the amide and/or the stabilisation that the nitrogen affords to the starting radical.

However, appropriate substitution can override this preference, and if a trimethylsilyl group is present on the terminal acetylene position, synthetically useful yields of the pyrrolizidinone can be obtained[39] (Scheme 17). Both of these observations are consistent with the guidelines of Beckwith[21] (Section IB1-2).

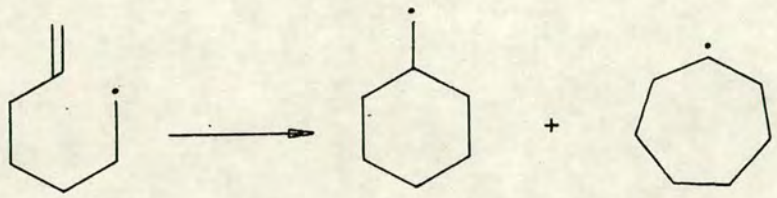


SCHEME 17

(ii) Six-membered rings

Two problems arise in the application of radical cyclisation methods to six-membered ring formation. First, 6-*exo* closure of the 6-heptenyl radical is more than one

order of magnitude slower than the analogous cyclisation of the hexenyl radical[23], thus the radicals can follow alternative reaction pathways. In addition, the increased chain length permits the formation of greater amounts of the *endo* product (43) (Scheme 18).



(43)

SCHEME 18

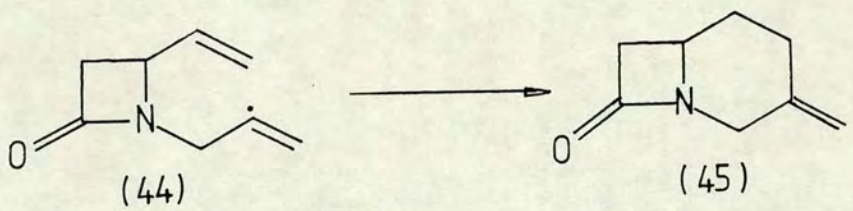
Secondly, allylic hydrogen abstraction through a 6-membered transition state can become a serious competing reaction.

Despite these problems, the formation of 6-membered rings can be achieved by appropriate precursor design. This includes: (1) the use of vinyl and heterovinyl radicals (eg $R-\dot{C}=O$, $R\dot{C}=NH$) and (2) the incorporation of certain heteroatoms, notably silicon or an amide group to afford the transition state, a geometry, in such a way that 6-*endo* cyclisation becomes favoured.

Vinyl radicals, usually generated by TBTH, are more reactive than related alkyl radicals, and are particularly valuable synthetically because an olefin suitable for further functionalisation is introduced with complete control of its location (eg Scheme 19). Furthermore,

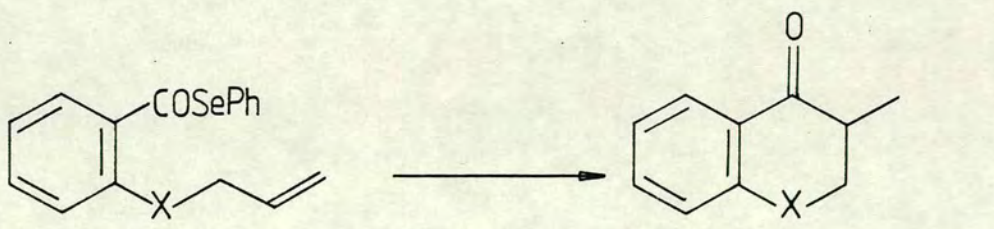
cyclisation is not dependent on the geometry of the starting vinyl halide because the barrier for the inversion of vinyl radicals is extremely low[41]. Therefore this species can be usefully applied to 6-membered heterocycle formation.

Parsons *et al*[40] have synthesised the carbacepham (45), a β-lactam antibiotic, in 58% yield, by the 6-*endo* cyclisation of a vinyl azetidinone radical (44) (Scheme 19[a]). No other cyclised products were detected.



SCHEME 19[a]

Similarly, 6-membered heterocyclic ketones (46) and (47) can be obtained in high yield, by the TBTH mediated 6-*exo* cyclisation of related carbonyl radicals[42] (Scheme 19[b]).



SCHEME 19[b]

In hex-5-enyl alkyl radicals, 6-*endo* cyclisation can be promoted by replacing C-3 with silicon[43]. However this process has limited effect because considerable 5-*exo* cyclisation also occurs and, more importantly, silicon-containing heterocycles have little general application.

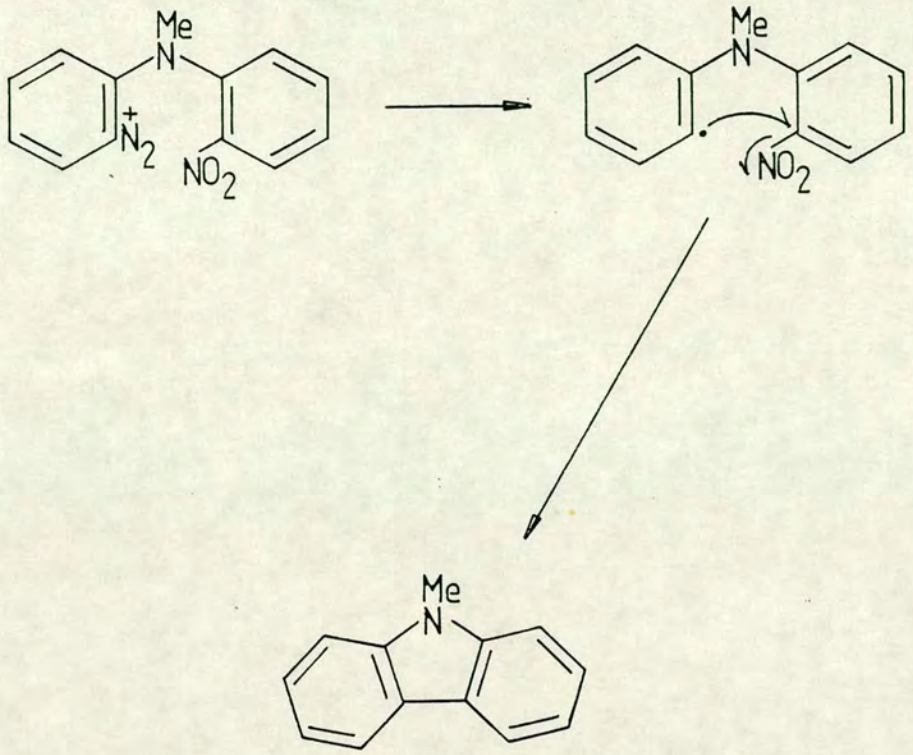
So far non-aromatic heterocycles have been considered, however high-yielding synthetic routes to aromatic heterocyclic systems are available. Obviously the reductive nature of TBTH-mediated reactions disfavours their use in this area, and generally cyclisation is achieved by the Pschorr reaction[16].

4. The Pschorr reaction

In this reaction bicyclic diazonium salts of suitable geometry (discussed in Section IA(v)) can lead to the formation of new rings via internuclear cyclisation.

There are several heterocyclic extensions of this reaction and these include the preparation of dibenzofurans[44], dibenzothiophenes[45], carbazoles[20] (48) (Scheme 20), and phenanthridones[46]. Yields range from moderate to high, the best usually obtained from stable diazonium fluoroborate precursors, however in some cases hydroxylation can compete with cyclisation and phenols can be formed[44,45].

Substituent groups appear to have no influence on the yield, except when the presence of an *ortho* substituent can block one of the positions of radical attack, although ejection of this substituent can also result[20] (Scheme 20).



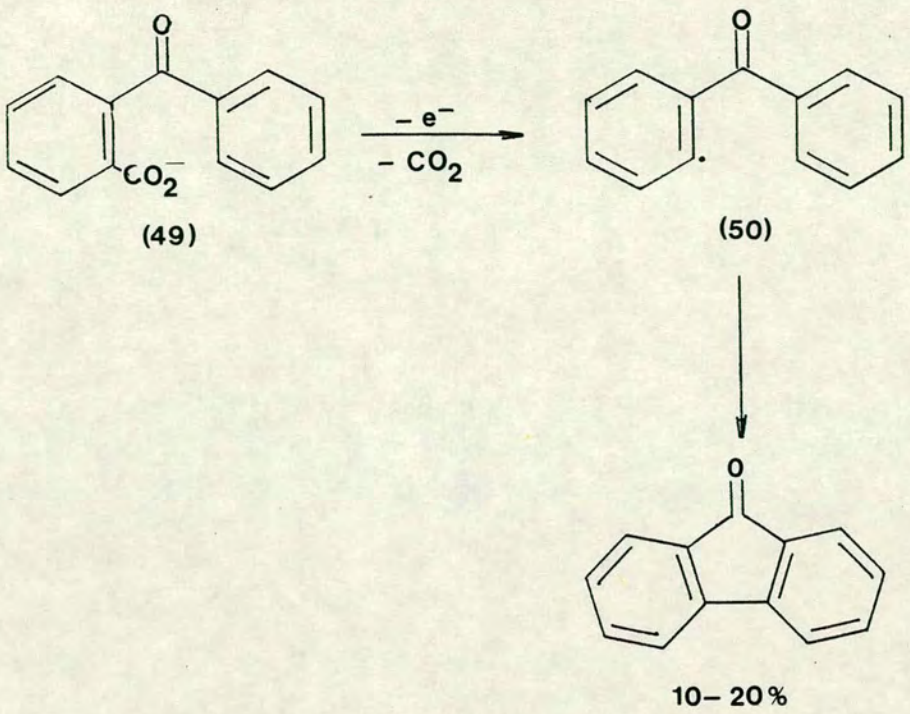
(48), 40%

SCHEME 20

5. Other internuclear free radical cyclisations

Such reactions have also been achieved (i) by the alternative generation of aryl radicals, (ii) from aroyloxy radicals, and (iii) from arylacyl radicals. These reactions can apply to both carbocycle and heterocycle formation and rings of 5, 6 or 7 members have been successfully prepared.

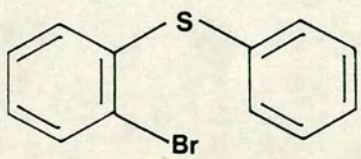
(i) Aryl radicals (50) can be generated from the salts of *o*-benzoylbenzoic acid (49) by electrolysis[47] or persulphate oxidation[48] (Scheme 21). However, in each case only a low yield of cyclised product is obtained.



(49) (50)

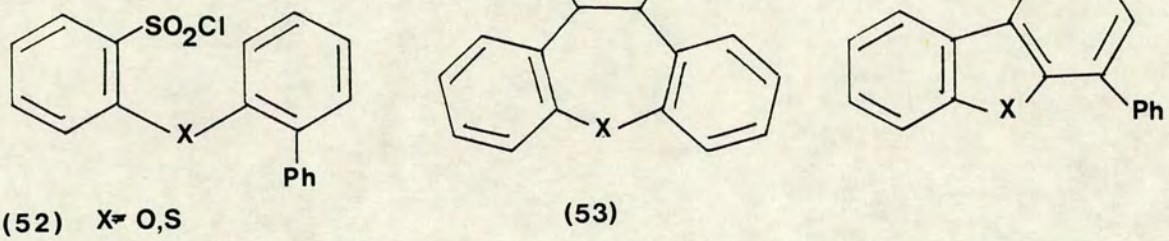
SCHEME 21

Similarly, heterocyclic ring-closures of this type have been described. Dibenzothiophene can be obtained in 10% yield, by the reaction of phenylhalides of type (51), with methylmagnesium iodide and cobaltous chloride[49].



(51)

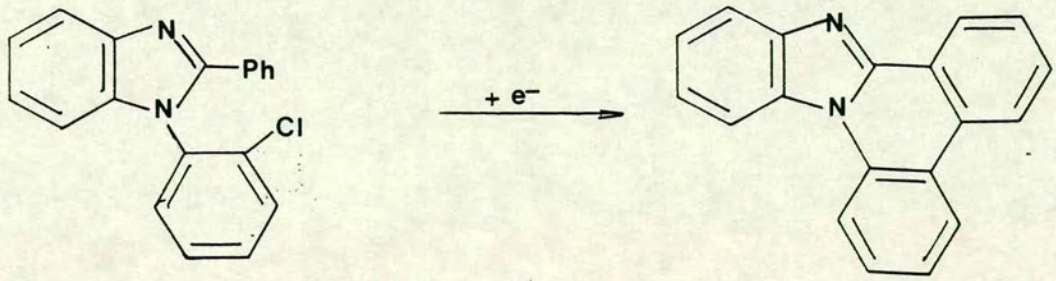
When sulphonyl chlorides of similar structure to (51) are heated at 250-260°C in an "inert" solvent such as octachloronaphthalene, the aryl radical is said to be produced[50] and cyclisation, in low yield, can result. Where the sulphonyl chloride precursor is suitably substituted, as in (52), the 7-membered ring product (53) may also be formed in yields of 40-50%[51] (Scheme 22).



(52) X= O,S (53)

SCHEME 22

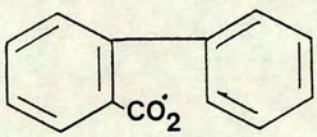
Recently Grimshaw[52] has reported the formation of a series of 6-membered nitrogen heterocycles (55) in yields of 80% (Scheme 23), obtained via the electrochemical reduction of easily prepared arylhalides (54) in highly dilute solutions in aprotic solvents.



(54) (55)

SCHEME 23

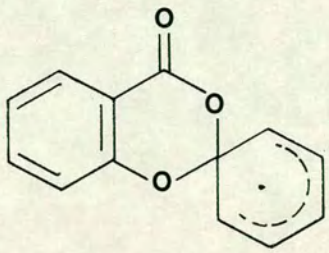
(ii) Aroyloxy radicals of type (56) can be generated from *o*-phenylbenzoyl peroxide in the presence of copper salts[53], these in turn can form 6-membered lactones. Similarly,



(56)

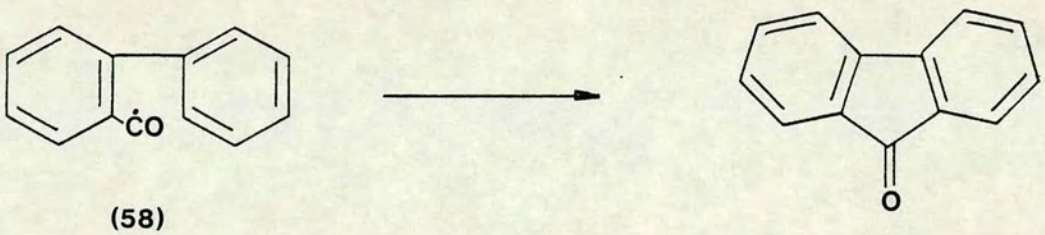
7-membered lactones can be obtained in low yield, by the oxidation of *o*-phenoxybenzoic acid with manganese dioxide[54].

Based on the evidence of rearrangement studies[47,55], the formation of a spirolactone intermediate of type (57) has been postulated in such cases to account for these observed products.



(57)

(iii) Arylacyl radicals of type (58) can be generated from *o*-phenylbenzaldehyde and di-t-butyl peroxide to give fluorenone (Scheme 24)[56] in low yield.



(58)

SCHEME 24

Similar cyclisations to those described in (i)-(iii), involving alicyclic systems and aralkyl radicals have been reported. Details of such reactions are beyond the scope of this report, but several reviews are available[57,58]. Furthermore, internuclear cyclisations generated in the vapour phase are discussed in the following section.

II VAPOUR PHASE REACTIONS

A. Flash vacuum pyrolysis (FVP)

Gas phase free radical reactions can be carried out under static conditions[59], in flow systems[60] or by flash vacuum pyrolysis[61]. The latter technique, which is discussed in this review, involves vaporisation of a substrate from an inlet system into a silica furnace tube, which can be maintained at temperatures up to 1000°C. The apparatus is kept under a vacuum of 10^{-2}-10^{-3}Torr and the products are collected in a liquid nitrogen trap situated at the exit point of the furnace. A diagram of the apparatus and further details of the method can be found in the experimental section of this thesis.

Despite the high temperatures involved, most functional groups can survive unchanged, because individual molecules only experience a short contact time (10-100ms) in the hot zone. The major advantage of such experiments is that under dilute gas-phase conditions, the radicals are generated in the absence of an excess of substrate, product or solvent molecules (ie effectively high dilution conditions), and thus intramolecular reactions are highly favoured.

The technique, in general, has been applied to three main categories of reactions:

(1) Symmetry-allowed retro-pericyclic processes, such as *cis*-elimination of esters[62] and retro-Diels Alder reactions[63].

(2) The extrusion of small molecules (eg CO_2, CO, N_2 and SO_2) from within a molecular framework, to give carbenes,

nitrenes or diradicals, which can undergo a wide variety of rearrangement reactions[64].

(3) The homolysis of the weakest single bond in the substrate molecule to generate two free radicals. Where substrate and conditions are carefully optimised the deliberate generation of free radicals can result, and therefore this is an ideal method for the induction of intramolecular cyclisations. The only appreciable intermolecular reactions occurring are the formation of neutral products by the coupling of radicals. Generally little mechanistic detail is known, although chain reactions do not occur because of the shortage of chain carriers.

Gas phase free radical intramolecular cyclisations have been applied to heterocycle formation, and the following sections will indicate (1) typical methods of generating free radicals by F.V.P., (2) the general mechanistic trends involved in these reactions, and (3) their synthetic applications, with respect to ring size.

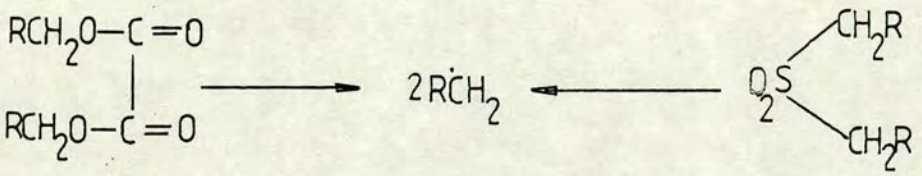
B. F.V.P.-mediated radical cyclisations

1. The generation of radicals by F.V.P.

This section aims to outline the common F.V.P. precursors of benzyl, phenyl, aminyl, iminyl, phenoxyl and thiophenoxyl radicals, together with their advantages and disadvantages. However a more detailed account of this subject is available in a recent review by Cadogan, Hickson and McNab[65].

(i) Carbon-centred radicals

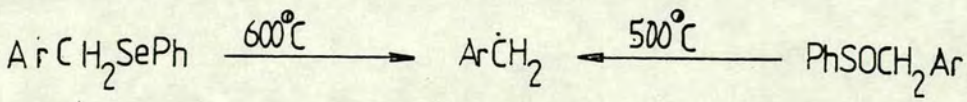
Benzyl radicals can be conveniently obtained from oxalates[66] (59) and sulphones[67] (60), the by-products being CO_2 and SO_2, respectively (Scheme 25). Temperatures in the range 550-750°C are required, however substrates containing bulky or polar groups can be involatile. In such cases selenides[68] (61) and sulphoxides[69] (62) can be



(59) (60)

SCHEME 25

employed as alternative benzyl radical generators (Scheme 26).

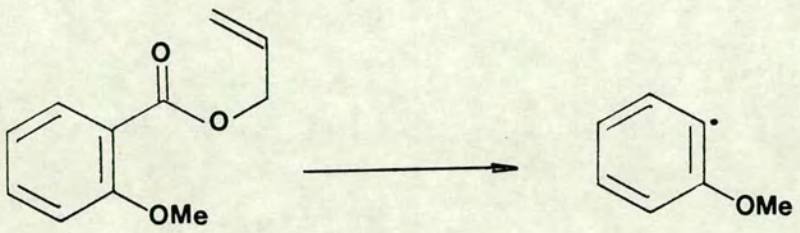


(61) (62)

SCHEME 26

Although phenyl radicals are common reaction intermediates, there is no well-defined and widely applicable method of generating these species in the gas phase.

Phenyl radicals can be obtained by the flow thermolysis of nitrobenzenes[70] by long contact time pyrolysis (*ca.* 10s), or by the flash pyrolysis of aromatic esters[71] (63) (Scheme 27).



(63)

SCHEME 27

However, the former case has found little general synthetic application and the latter requires extreme furnace temperatures (>850°C).

(ii) Nitrogen-centred radicals

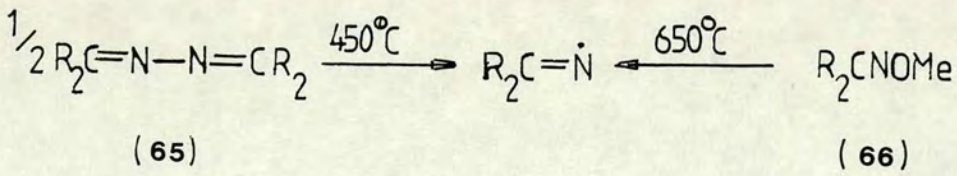
The generation and reactions of aminyl radicals in the gas phase have largely been studied by McNab *et al* [72]. Throughout this work the radicals studied have been generated from the appropriate *N*-allyl derivative (64) (Scheme 28). The substrates are easily obtained, in

(64)

SCHEME 28

reasonable yields by the reaction of the appropriate amine with allyl bromide in basic solution. However chromatography is required to remove a small amount of the *N*,*N*-diallyl derivative[72].

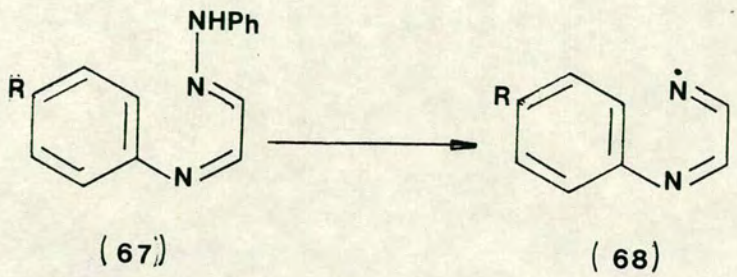
Iminyl radicals are readily generated from a variety of hydrazones and oxime derivatives[73] (Scheme 29). The azines (65) give rise to few by-products and are the favoured precursors for relatively low molecular weight iminyls[73]. For larger molecules, oxime ethers (66) are conveniently volatile and there is little interference from the co-formed alkoxyl radical[74]. A detailed study



(65) (66)

SCHEME 29

has been made of the reactions of conjugated iminyl radicals (68)[75], obtained by pyrolysis of mixed hydrazone imines of α-dicarbonyl compounds, eg (67) (Scheme 30), and this is detailed in the Section II.B.2.

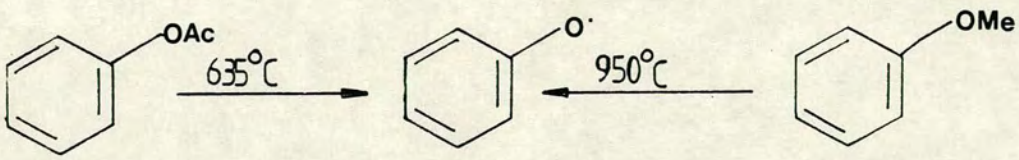


(67) (68)

SCHEME 30

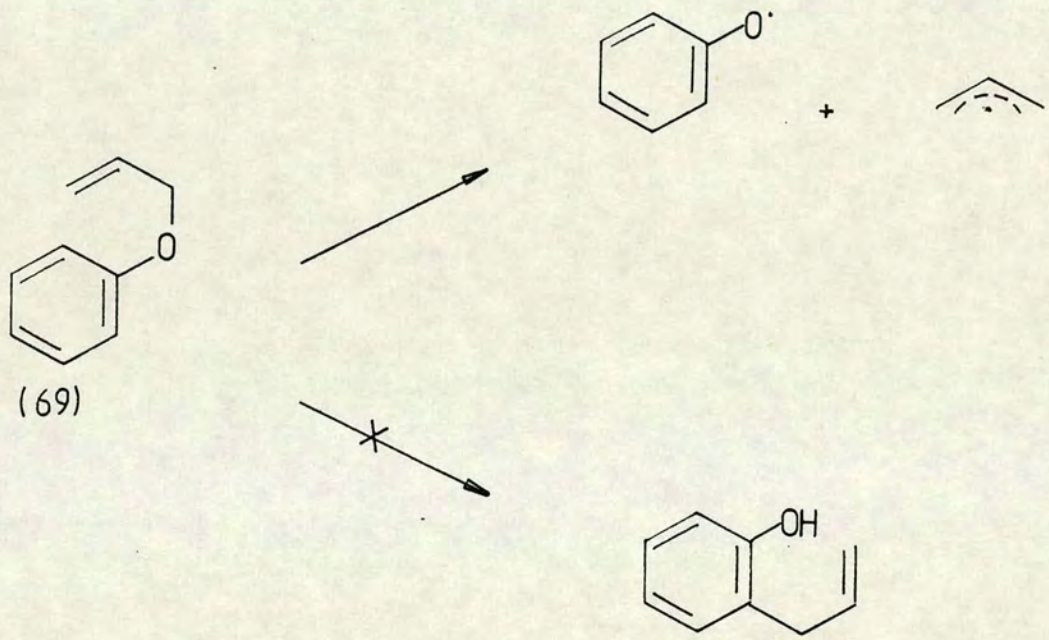
(iii) Phenoxyl radicals

Methods of generating these species by F.V.P. have not been well investigated, although it appears that phenoxyl radicals can be easily obtained from several molecules containing this structural unit[76,77] (eg Scheme 31).



SCHEME 31

However, the appropriate aryl allyl ether (69) provides a more convenient precursor to these species[78] (Scheme 30). Surprisingly the Claisen rearrangement does not appear to compete with homolysis under F.V.P. conditions, possibly because of its unfavourable activation entropy[79] (Scheme 32).

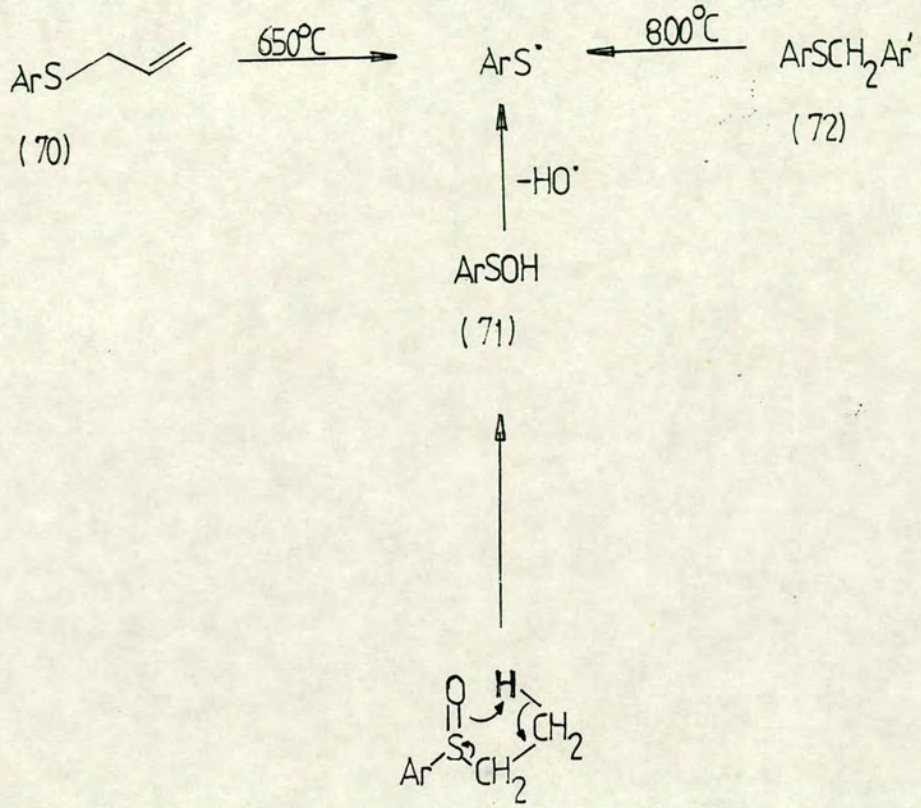


SCHEME 32

(iv) Thiophenoxy radicals

These species, like the aminyl and phenoxyl radicals, can be obtained from the appropriate allyl ether[78] (70) (Scheme 33). However thiophenoxyl radicals are also generated as a by-product of the preparation of sulphenic acids (71) by sulphoxide pyrolysis[80], or directly by the

pyrolysis of thioethers[79] (72) (Scheme 33).



SCHEME 33

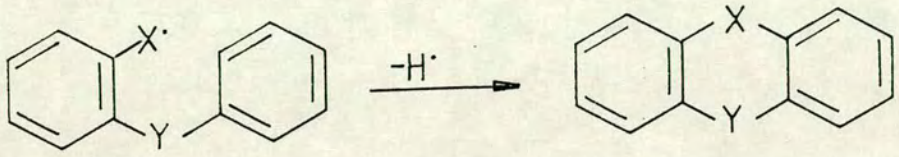
Once generated, these aromatic free radicals can undergo a variety of reactions, however only intramolecular cyclisations are considered in the following sections.

2. Gas phase free radical cyclisations. General mechanisms

Unlike the corresponding solution-phase chemistry, very little work has been done in this area, and mechanistic guidelines are not available. However general mechanistic trends have been rationalised from the systems investigated

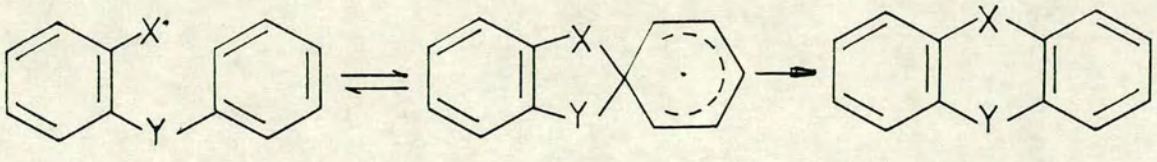
and these are discussed below.

In several reactions, product ratios have suggested that intramolecular cyclisation may proceed directly (Scheme 34) or via a competing rearrangement process,



SCHEME 34

involving a spirodienyl intermediate (73) (Scheme 35) [cf Section IB5(ii)].

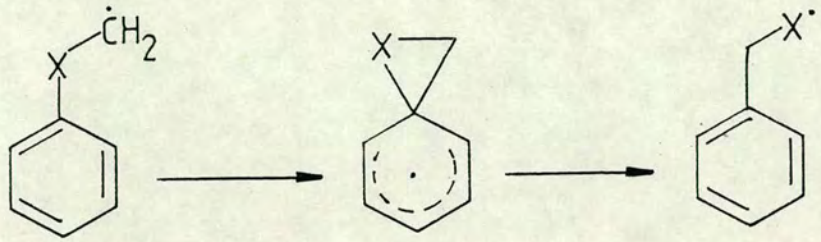


(73)

SCHEME 35

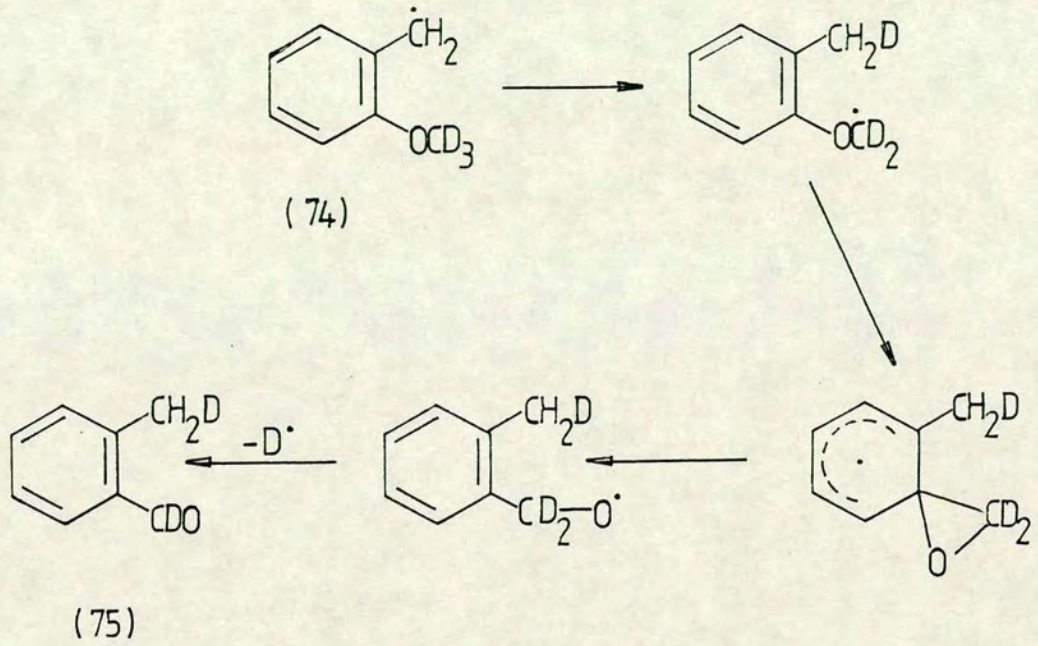
Spiro-intermediates containing 3 and 5-members have been studied. The formation of 3-membered systems is neatly illustrated by the neophyl rearrangement[57] (Scheme 36), where spiro formation results from the attack of a

β-radical on an aromatic ring. The spiro-intermediate can then open in the opposite sense. The β-radical may be generated by H-shift from a phenyl, benzyl or related



SCHEME 36

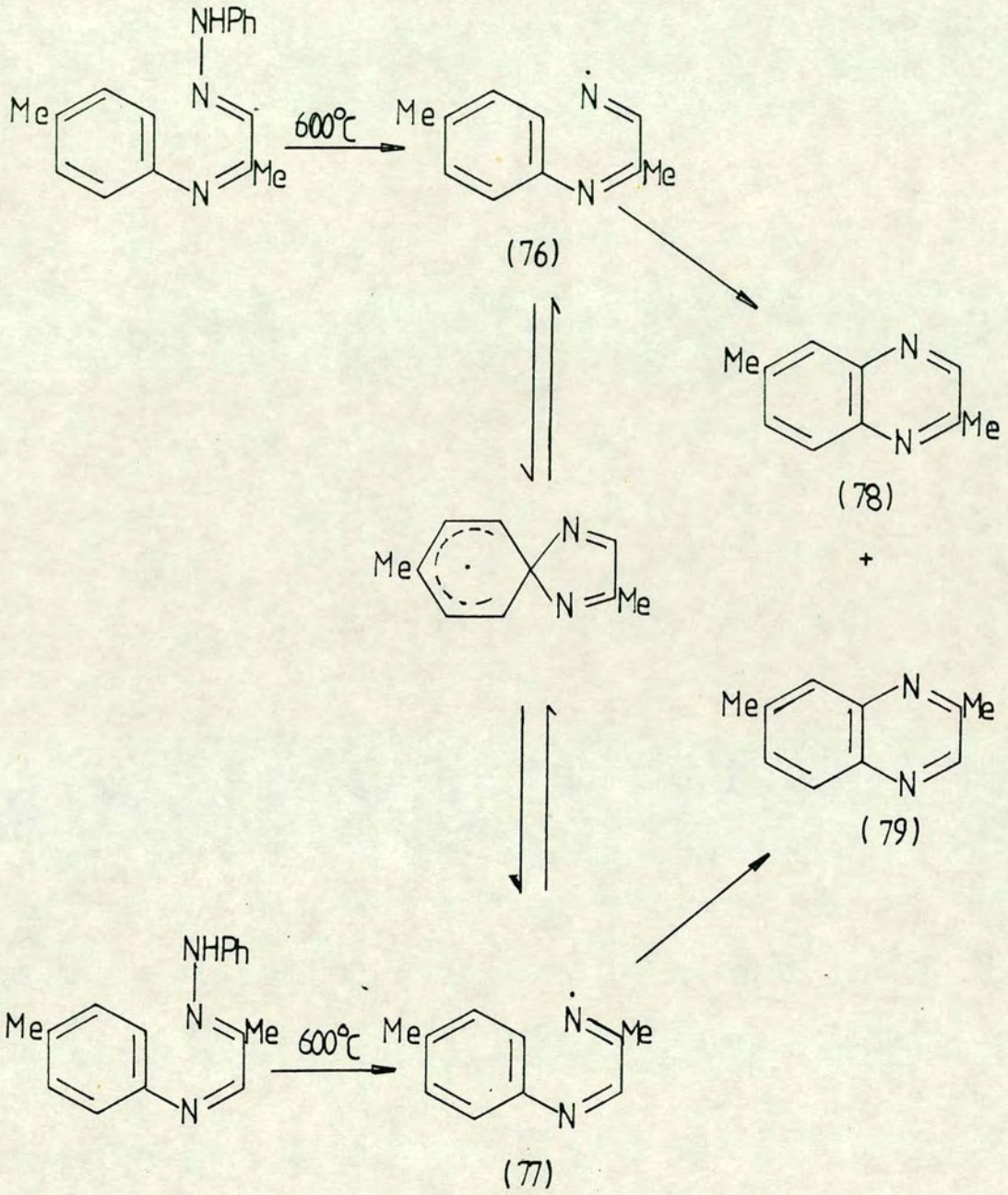
radical. This has been demonstrated by McNab *et al.*[81], wherein the generation of the 2-[D_3]-methoxybenzyl radical (74) resulted in the formation of (75), with the label being equally distributed between the aldehyde and methyl groups (Scheme 37).



SCHEME 37

Phenoxyl radicals behave analogously, but complications arise, where either of the *ortho* substituents contain sulphur atoms[81].

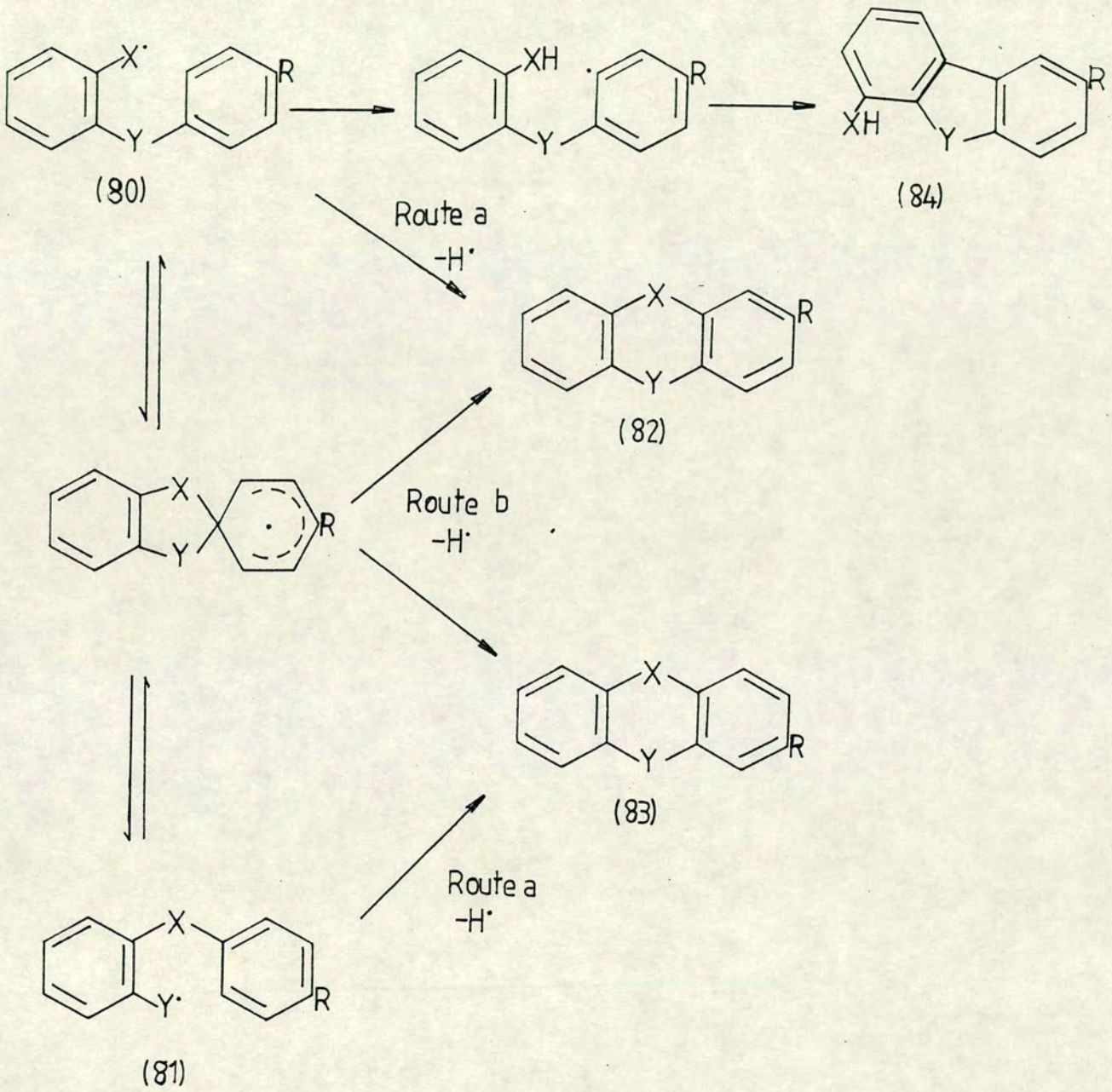
McNab and co-workers have also studied cyclisations which may proceed via a 5-membered spirodienyl intermediate. This can be illustrated by the approximately equal formation of two isomeric quinoxalines (78) and (79) from the generation of either of the iminyl radicals (76) and (77) (Scheme 38)[75]. Further investigations of


NHPh
N
Me
Me
N
600°C
Me
N
Me
N
(76)
Me
N
Me
N
(78)
+
Me
N
N
Me
Me
N
Me
N
(79)
NHPh
N
Me
Me
N
600°C
Me
N
Me
N
(77)

SCHEME 38

the reaction mechanism by ^{15}N labelling studies[82] have found that the label was scrambled between both nitrogen sites of the quinoxalines, thus confirming the involvement of the spiro-intermediate.

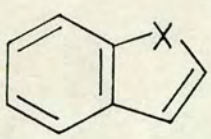
Similarly, labelling studies[83] have indicated that systems of general type (80) and (81), where X and Y are a variety of heteroatoms, can also cyclise via a spiro-intermediate, to the fused 6-membered products (82) and (83) (Scheme 39). However formation of the 5-membered ring product (84) results from a competing hydrogen abstraction reaction, which is further complicated by heteroatom effects[84], and thus these systems are generally poor synthetic precursors.


X·
R
Y
XH
R
Y
R
XH
Y
(80)
(84)
Route a
-H·
X
R
Y
(82)
X
Y
R
Route b
-H·
X
R
Y
(83)
Route a
-H·
X
Y·
R
(81)

SCHEME 39

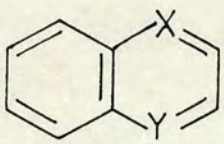
3. Applications to heterocycle formation

Gas phase radical cyclisations have been applied to heterocycle formation and several synthetically useful reactions are known. Routes to fused 5- and 6-membered heterocycles of types (86), (87) and (88) are available, and are discussed below. However, unlike the related solution-phase reactions (Section IB5), there is no precedent for 7-membered ring formation.



(86)

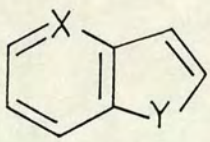
X = O, S, NH



(87)

X = O, S, N

Y = N, CH

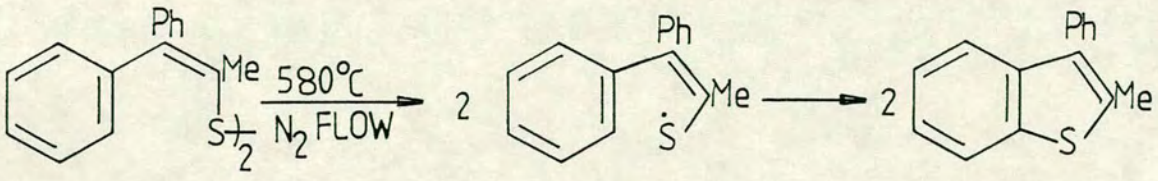


(88)

X = N

Y = O, S

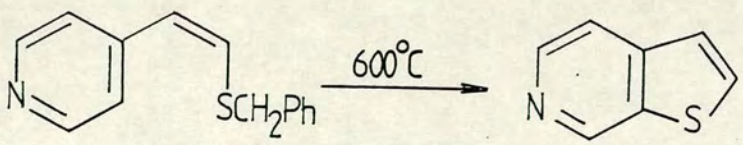
(i) Five-membered rings. Work in this area is limited and few general routes have been reported. Benzothiophenes[85] can be prepared in 40-90% yields via the generation of a range of conjugated radicals (88), from either sulphides, disulphides or sulphoxides (Scheme 40). Minor quantities of hydrocarbon by-products may also be formed, due to sulphur extrusion from (88) or by alternative cleavage of the precursor. Similarly, the



(88)

SCHEME 40

related thienopyridine system can be prepared in high yield (>60%) by cleavage of the weak *S*-benzyl bond in the unsaturated benzyl pyridyl sulphide precursor (89), under standard F.V.P. conditions (Scheme 41).

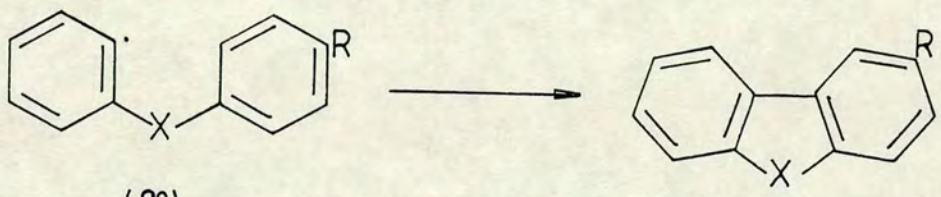


(89)

SCHEME 41

Ring closure can also be achieved by carbon-carbon bond formation. Hence a synthetically-viable route to

a range of 2-substituted dibenzothiophenes and dibenzofurans has been reported[87]. This involves the generation of a σ phenyl radical (90), directly, from the appropriate allyl ester at 900°C (Scheme 42). However the reaction is limited because some functional groups (eg OMe) cannot tolerate the high temperature required for homolysis and complications can arise with *ortho*- and *meta*-substituted precursors. Furthermore,



(90)

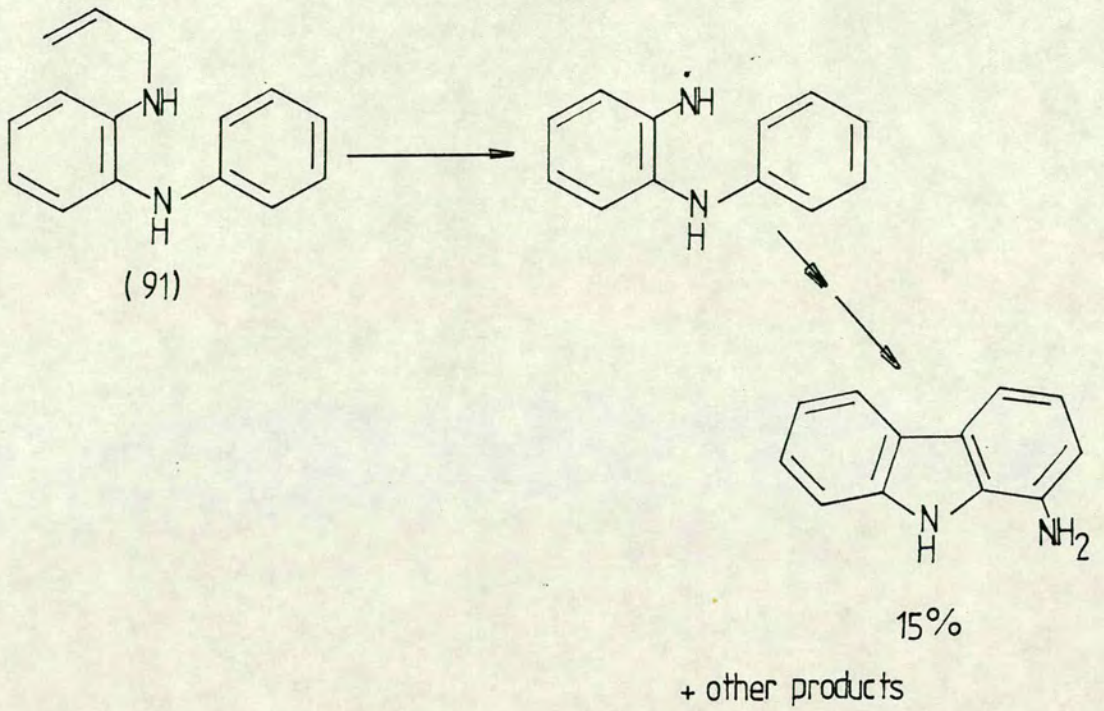
X= O,S

R=H,Me,Cl,COMe

30-60%

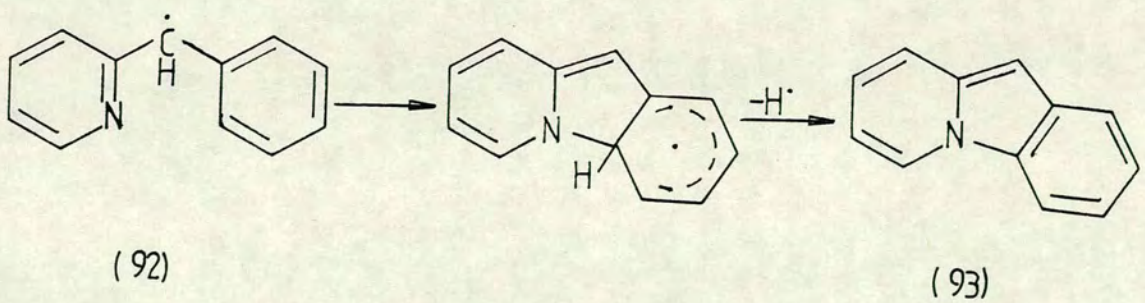
SCHEME 42

attempts to extend this reaction to carbazole and fluorene preparation have proved unsuccessful[88]. However 1-aminocarbazole can be obtained, as a minor product, in the pyrolysis of 2-(allylamino)diphenylamine[89] (91), possibly via the H-abstraction and cyclisation reaction pathway described in Section IIB2 (Scheme 43). Obviously this is a non-viable route to such compounds.



SCHEME 43

On the other hand, the benzo[b]indolizine system (93), containing a similar heterocyclic unit, can be synthesised in yields of 40-50% by the cyclisation of phenyl 2-picolylmethyl radicals (92) (obtained from N-oxide pyrolysis)[88] (Scheme 44).

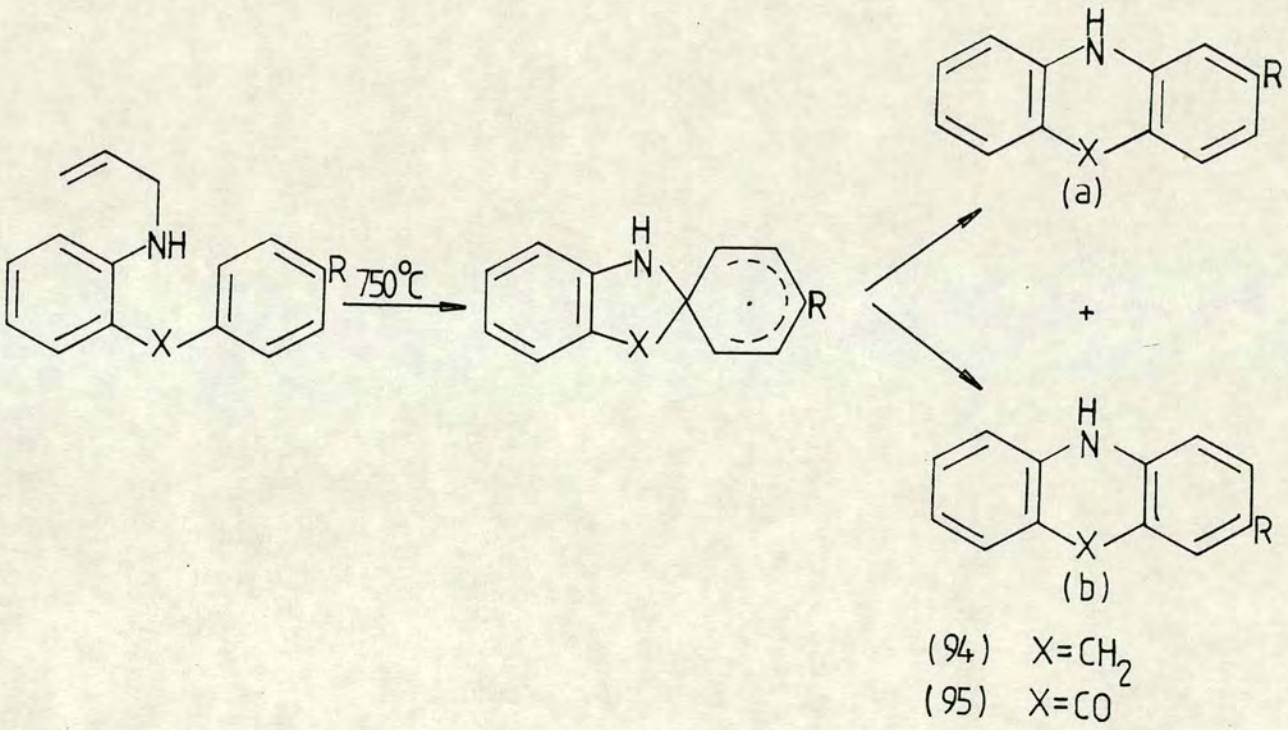


SCHEME 44

This reaction has also been applied to a range of heterocyclic systems derived initially from quinoline, isoquinoline and diazine N-oxides[89].

(ii) Six-membered rings

Synthetic routes to 6-membered rings containing either one or two heteroatoms, have been reported. Firstly, acridan (94) and acridone (95) can be obtained in yields of 60-80% by pyrolysis of the appropriate N-allyl compound[89], (Scheme 45). Although no 5-membered

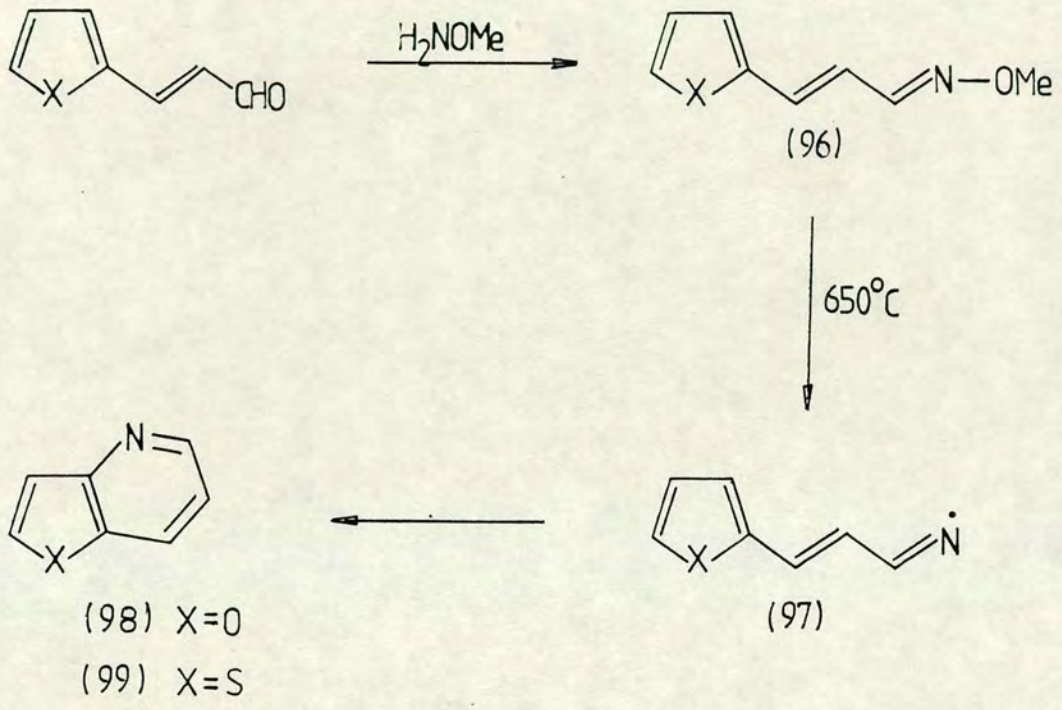


SCHEME 45

ring products are obtained, the formation of the isomeric mixture (94 and 95 a+b) indicates that cyclisation proceeds via a spiro-intermediate (Scheme 45).

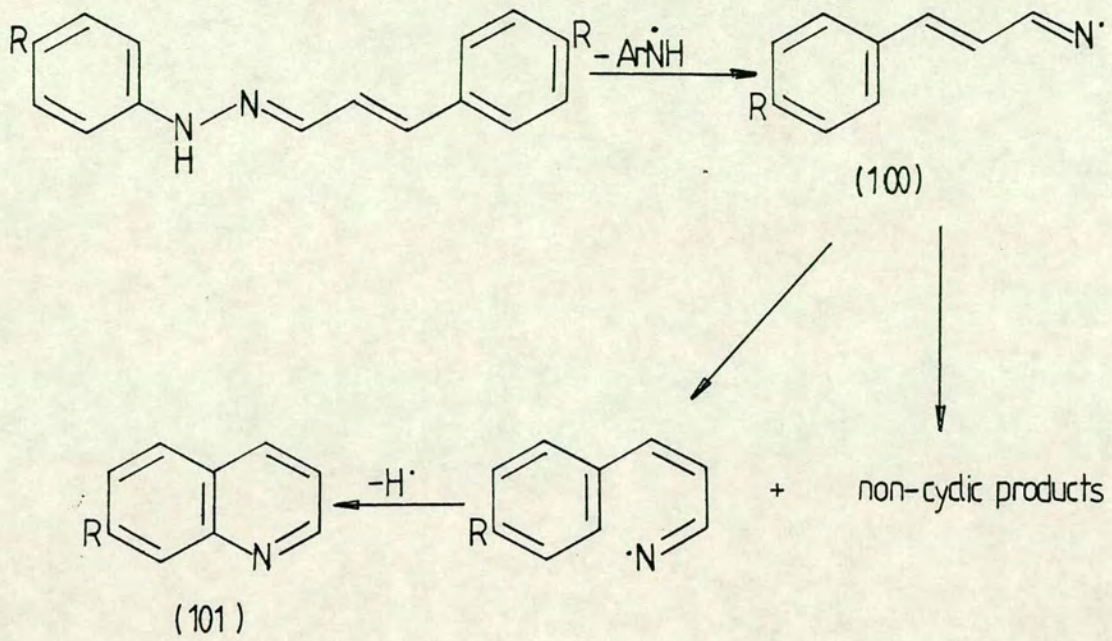
In contrast, direct cyclisation may account for the formation of isomerically-pure furo (96) and thienopyridine

(97) systems; in a convenient one-step process from the readily available oxime ethers (96), via the conjugated iminyl radical (97)[90], (Scheme 46). However, yields are low (20-30%) and a better F.V.P. route to the thieno[3,2-b]pyridine system has been developed by Klemm *et al.*[86], previously discussed in Section IIB3(i).



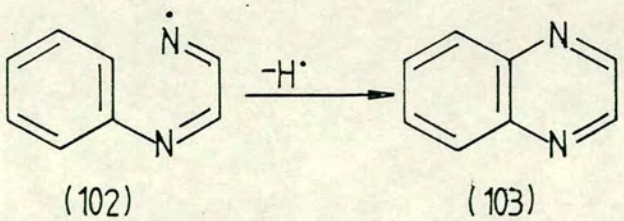
SCHEME 46

Formation of the quinoline system (*ca.*20%) by cyclisation of the appropriate iminyl radical (100) (derived from the cinnamyl hydrazone or oxime ether) may also proceed by direct cyclisation as no rearrangement has been detected[74] (Scheme 47). Cinnamonitriles, formed by β-cleavage of the iminyl, are significant by-products, however the reaction is synthetically useful, because it is the only specific method of forming 7-substituted quinolines (101) (Scheme 47).



SCHEME 47

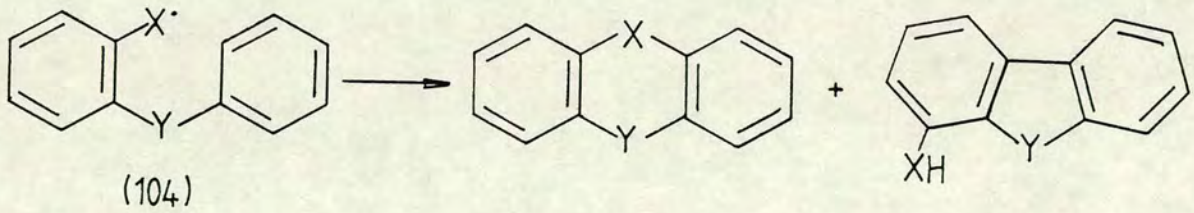
Cyclisation of the related conjugated iminyl radical (102) provides a route to the quinoxaline structure[91] (103, *ca.*30%) (Scheme 48). Investigation of the mechanism of this reaction, discussed in Section IIB2 (Scheme 38) has indicated that cyclisation proceeds via a spirodienyl intermediate,[82] thus permitting rearrangement of the initial radical.



SCHEME 48

The specificity of this reaction can be affected by the substitution pattern of the precursor. Thus the presence of an *ortho*-substituent, in the 5-aryl ring, leads to two cyclic products, formed either by reaction at the free *o*-site or by *ipso* attack followed by ejection of the substituent[92]. *Ipso* attack is favoured by *o*-OMe substituents, while straightforward cyclisation affords the major product for *o*-Me, and *o*-chloro substituents. Two quinoxalines are also obtained on pyrolysis of *m*-substituted precursors, except where the substituent is an alkyl group, in which case the iminyl radical preferentially attacks the position *para* to the substituent[92].

Rearrangement via a spiro-intermediate has also been implicated in the cyclisation of the radical system (104), where X and Y are a range of heteroatoms[83], (see Section IIB2).



(104)

SCHEME 49

Thus a mixture of 5- and 6-membered heterocyclic systems can be obtained (Scheme 49). However the route has little synthetic viability because yields of each component are low (<20%) and isomeric mixtures of 6-membered products may result with certain precursors[83].

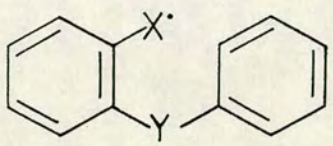
SUMMARY

It is apparent that much work has been done in the area of condensed-phase free radical cyclisations, so that mechanistic guidelines are available, and thus many synthetic routes to heterocyclic systems have been developed. However, vapour phase cyclisations have received much less attention, and although the systems studied have revealed interesting mechanistic details, only a few synthetically viable reactions are known. However, in this thesis, several new synthetic routes to heterocyclic systems are reported, and mechanisms have been proposed in relation to previous work carried out in this area.

DISCUSSION

A Introduction

During the work carried out by Hutchison[87], the generation and cyclisation of the radical system (105) was studied, where X and Y are a variety of hetero-atoms. From each of these radicals a series of both



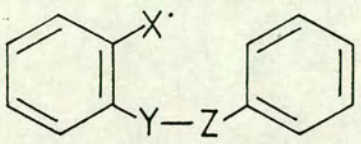
(105)

X = NH, S, O, CH_2

Y = NH, S, CO, CH_2

5- and 6-membered heterocyclic ring systems were obtained (discussed in the Introduction). Mechanistic investigation of these reactions[87] indicated that: (1) cyclisation to the 6-membered ring may proceed directly or *via* a spirodienyl intermediate, and (2) formation of the 5-membered products may occur *via* a competing hydrogen abstraction reaction, to generate a phenyl radical, which can then cyclise directly (Scheme 37).

This work has been extended to the radical system (106), and the investigation of these reactions is reported in this thesis.



(106)

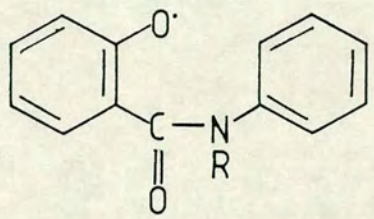
Phenoxyl (106, X=O) and thiophenoxyl (106, X=S) radicals have been generated from the corresponding allyl or isopropyl derivative, and a series of linkages (Y-Z), comprising amides, esters, azo compounds, imines and olefins have been studied.

Investigation of this radical system had two main objectives. Firstly, it was hoped that new routes to fused heterocyclic systems could be developed, and secondly to determine if these cyclisations also proceed by either a H. abstraction reaction or *via* a spiro-intermediate.

Consequently, several new synthetic routes have been developed, and mechanistic details have been rationalised from the observed products. In the following sections each linkage type (Y-Z) is discussed separately, although mechanistic and synthetic trends will become apparent.

B Generation and Cyclisation of (2-*N*-Substituted-carbamyl)phenoxyl radicals

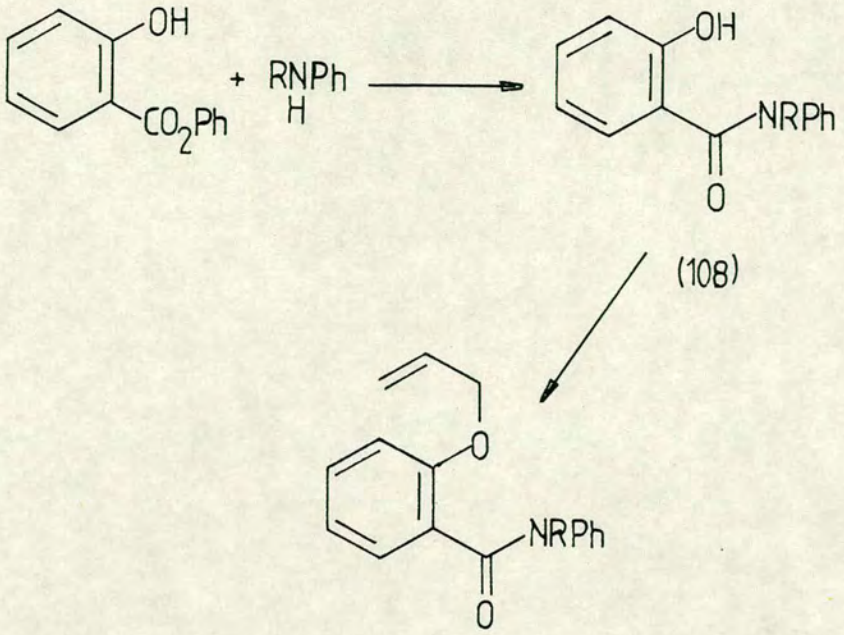
The title species (107) were generated by the pyrolysis of the appropriate *O*-allyl derivatives. These precursors were obtained by reaction of the



(107)

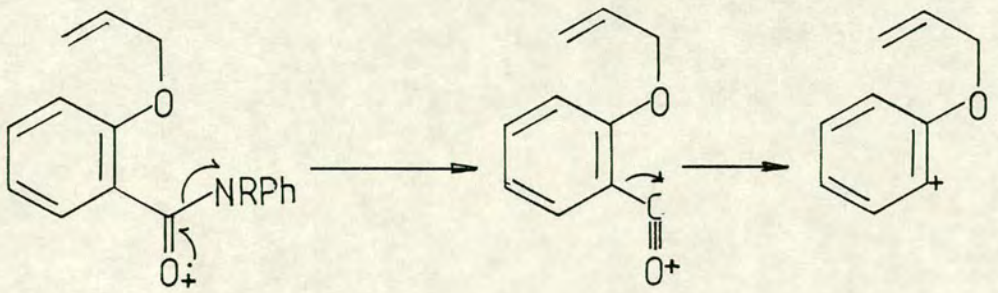
R = H, Me, Et, Ph

required aniline with phenyl salicylate to give the desired *O*-hydroxybenzamide (108), followed by *O*-alkylation of (108) with allyl bromide, under basic conditions (Scheme 50[a]). Alkylation proceeds quantitatively in all cases, however the yield of the hydroxy compound is lower where bulky amines are used.



SCHEME 50a

The mass spectra of the *O*-allyl derivatives (109), differs from their expected thermal breakdown, as the major fragmentation involves cleavage of the amide bond to give a base peak at *m/z* 161, followed by loss of CO, producing a peak at *m/z* 133 (Scheme 50[b]).



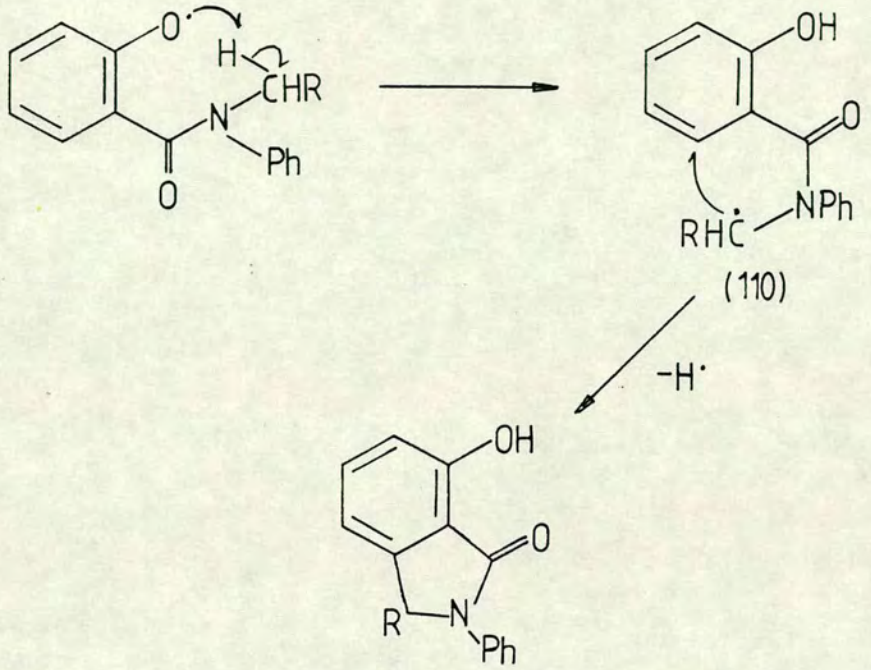
(109)

SCHEME 50b

However, these precursors did not all behave the same way under FVP conditions. Pyrolysis of the *N*-methyl derivative (109, R=Me) at 650°C afforded a crystalline solid, whose ^{1}H n.m.r. spectrum revealed the presence of eight aromatic protons and a deshielded methylene group at δ_H 4.80. The ^{13}C (D.E.P.T.) n.m.r. spectrum verified the presence of a methylene signal at δ_C 51.11, and mass spectrometry indicated a molecular weight of 225, with a fragmentation pathway involving loss of a hydroxyl group to give a peak at M-17. Furthermore, CHN analysis and correlation with a literature melting point[93] indicated that 2,3-dihydro-7-hydroxy-2-phenylisoindol-1-one (111, R=H, 33%) had been obtained.

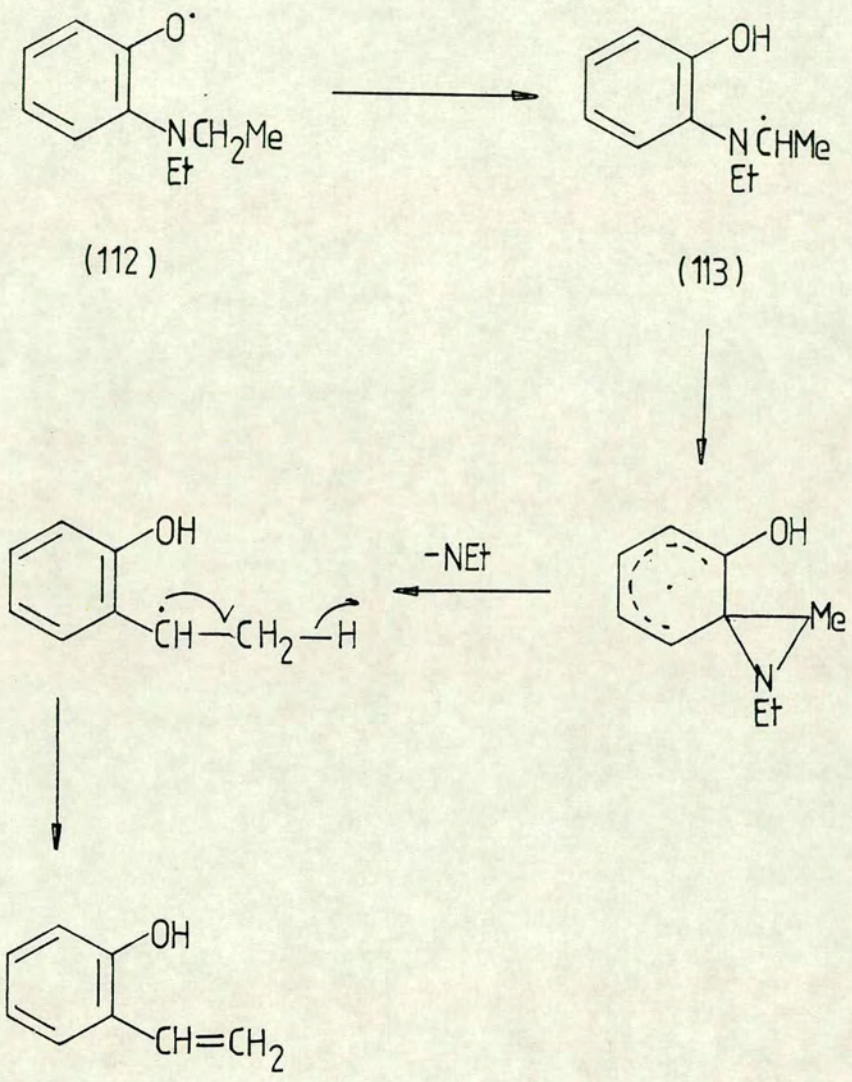
Formation of (111) suggests that the initial phenoxyl radical may abstract a hydrogen atom from the nearby alkyl group, through a 7-membered transition

state, thus forming the stabilised aminomethyl radical (110), which can then cyclise directly (Scheme 50[c]).



SCHEME 50c

Hydrogen abstraction *via* a 6-membered transition state has been reported for the related *o*-diethylaminophenyl radical[94] (112, Scheme 51). However in this case, direct cyclisation of the resulting aminomethyl radical (113) (to the 4-membered ring) is not observed. Instead *o*-hydroxystyrene is obtained by fragmentation of (113), *via* a 3-membered spiro-intermediate[94] (Scheme 51), (see Introduction, Section II.B.2).

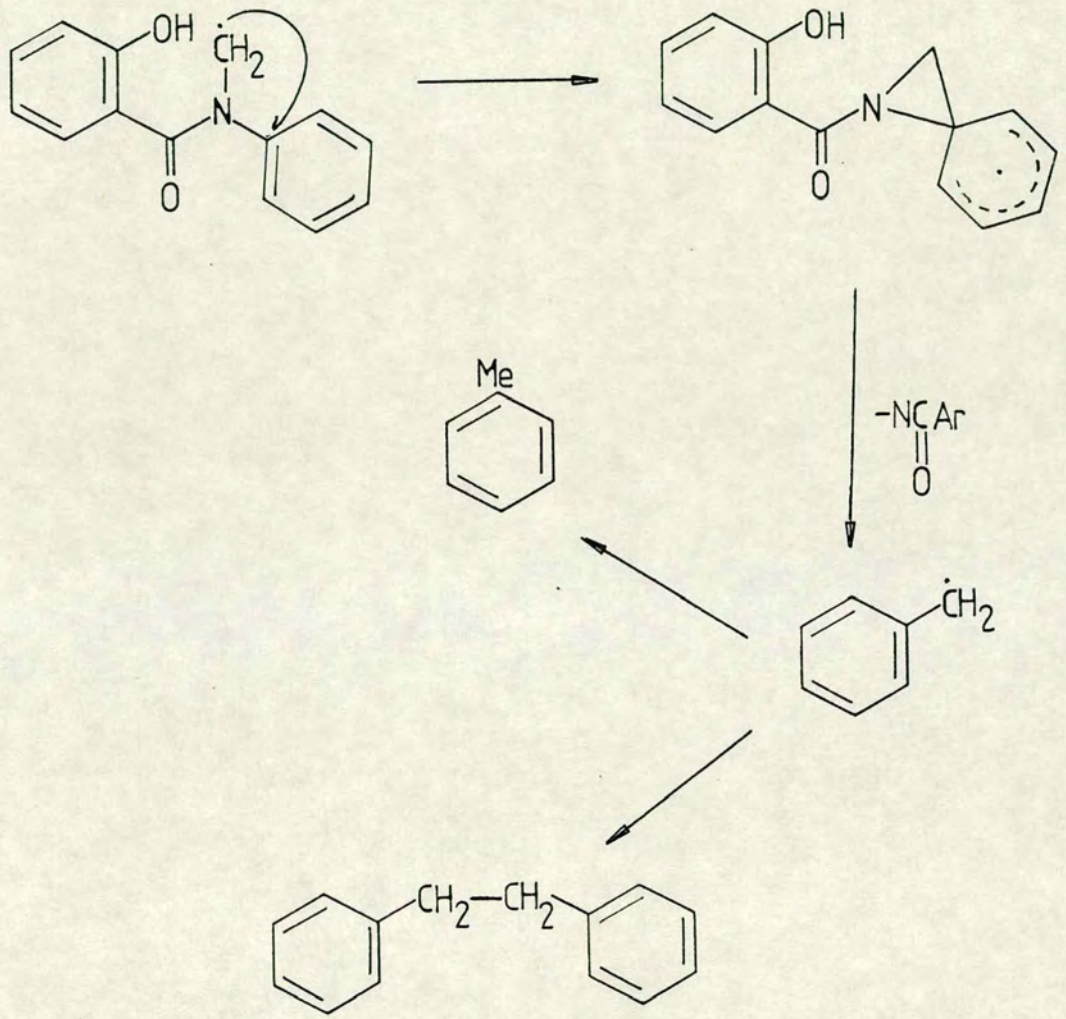


(112)

(113)

SCHEME 51

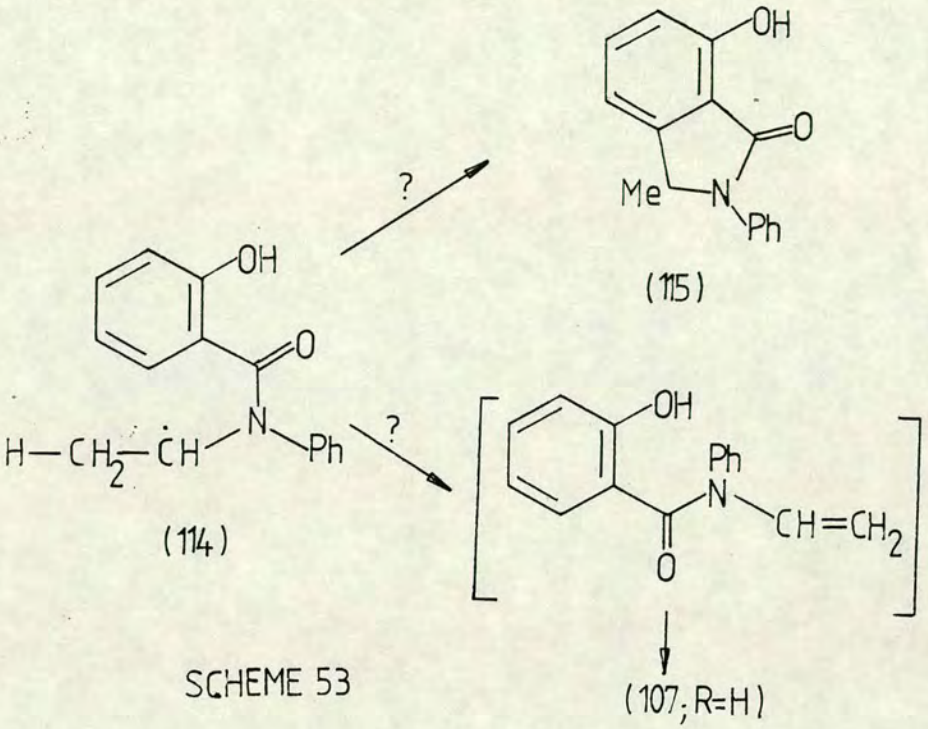
Spiro-intermediate formation could also occur in the *N*-methylbenzamide system, where fragmentation of the aziridine ring could produce toluene or bibenzyl, (Scheme 52), however neither of these compounds have been detected by g.c.



SCHEME 52

Pyrolysis of the *N*-ethylbenzamide precursor was then investigated because this aminoalkyl radical (114), if formed, has the option of direct cyclisation to the

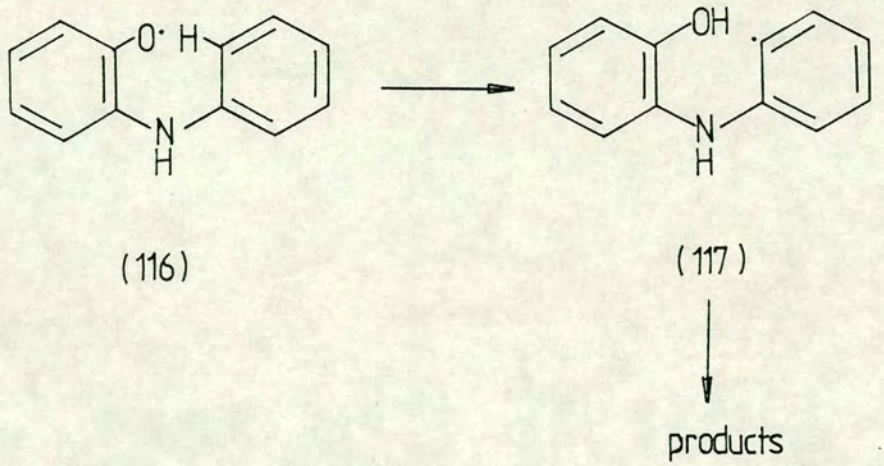
isoindolone or fragmentation to the enamine (Scheme 53). However, pyrolysis afforded a crystalline solid,



SCHEME 53

whose ^1H n.m.r. spectrum indicated the presence of a methine as a quartet at δ_H 5.20 coupled to a methyl group, a doublet at δ_H 1.44, thus suggesting the formation of 3-methyl isoindolone (115, 29%). No other significant products were detected, and this would suggest that direct cyclisation of (114) is kinetically-favoured over fragmentation, although cleavage products of (114) may undergo polymerisation and therefore have not been detected.

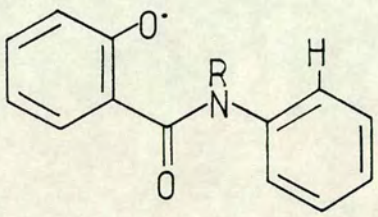
If we reconsider the radical system (107) it is notable that reaction proceeds by a H-abstraction involving generation of the stabilised aminomethyl radical (eg 110, Scheme 50) whereas formation of the phenyl-radical (117), as observed by Hutchison[83] in the related amino-bridged phenoxyl system (116) is not indicated, (Scheme 54).



(116) (117)

SCHEME 54

Therefore radical systems (118, R=H) and (119, R=Ph), with no available alkyl hydrogen atoms, were generated to determine if aryl hydrogen abstraction could proceed *via* an 8-membered transition state.

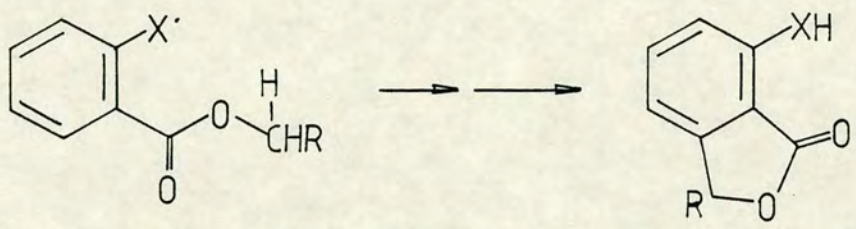


(118) R= H
(119) R= Ph

However, generation of (118) required a high temperature (>850°C), with only polymeric products being formed, whereas no cyclised products were obtained from (119), although g.c./m.s. indicates that diphenylamine *m/z* 169, is produced. This suggests that hydrogen-transfer in this system may be disfavoured because of the inherent geometrical constraints and therefore these systems preferentially undergo fragmentation and/or polymerisation.

C Generation and Cyclisation of (2-Alkyloxycarbonyl)-phenoxyl and (2-Alkyloxycarbonyl)thiophenoxyl radicals

It was hoped that radicals of type (120 and 121) would undergo a cyclisation analogous to the benzamide system (described in the previous section), thus producing the 7-hydroxyphthalide structure (122, Scheme 55), analogues of which are known to occur as components

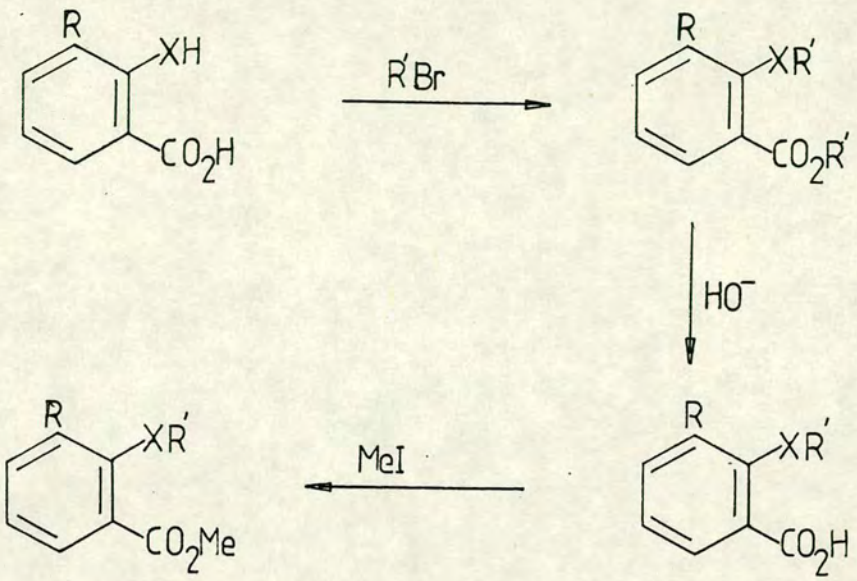


(120 ; X = O)
(121 ; X = S)

(122 ; X = O)
(123 ; X = S)

SCHEME 55

of natural products[95,96]. However work reported in this thesis is concerned with the reaction of simple (alkyloxycarbonyl)phenoxyl (120) and (alkyloxycarbonyl)-thiophenoxyl (121) radicals, which are generated from the corresponding allyl or isopropyl derivative. The precursors are prepared from the appropriate ester by the standard alkylation conditions used previously or, in the case of (124) and (125), by the method depicted in Scheme 56.



(124; X=O; R=Me; R'=CH_2=$CHCH_2$–)

(125; X=S; R=H; R'=^{i}Pr)

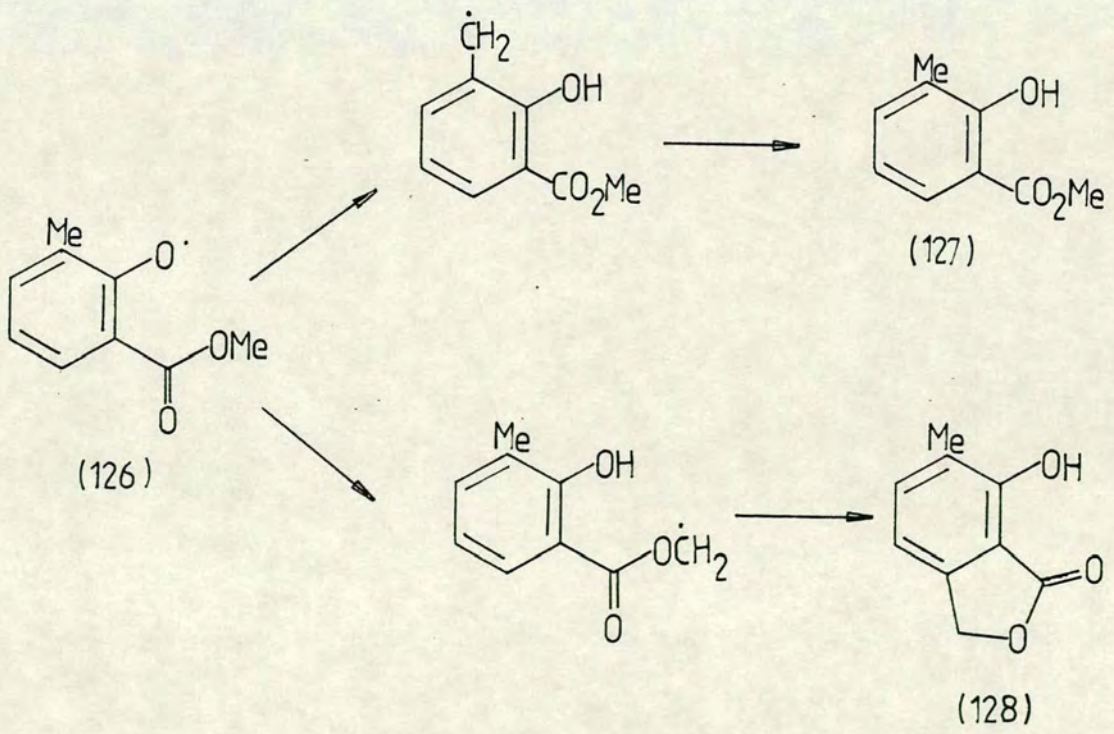
SCHEME 56

The mass spectra of the allyl and isopropyl compounds show a similar fragmentation pattern to the benzamide system (Section B, Scheme 50[b]) which indicates α-cleavage of the ester linkage, with peaks at M-OR followed by loss of carbon monoxide.

Generation of the (2-methyloxycarbonyl)phenoxyl radical (120, R=H) at 650°C (10^{-3} Torr) produced an oily fraction, composed of polymeric material, and a crystalline solid identified as 7-hydroxyphthalide (122, R=H, 25%) (Scheme 55), by correlation with a literature melting point[97]. This suggests that the mechanism proposed for the isoindolone formation (see Section B) can also occur in these systems. Similarly, generation of the (2-methyloxycarbonyl)-thiophenoxyl radical (121, R=H) at 750°C (10^{-3} Torr),

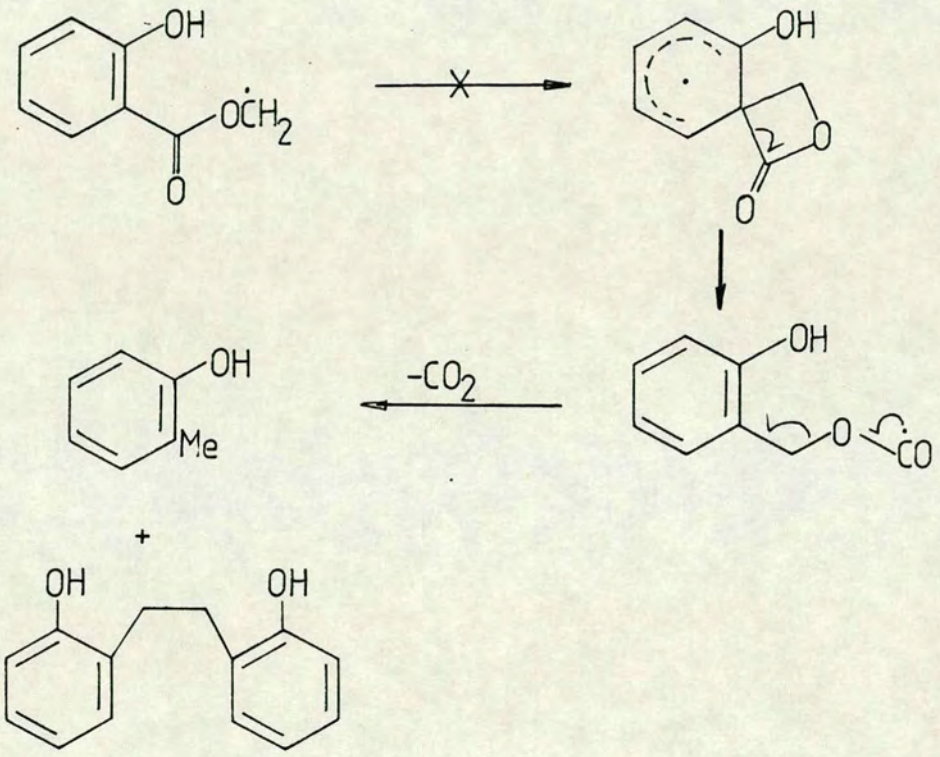
afforded a solid whose ^{1}H n.m.r. spectrum reveals the presence of three aromatic protons, a thiol signal at δ_H 6.25 and a methylene signal at δ_H 5.24, consistent with the formation of 7-mercaptophthalide (123, R=H, 18%), by this route.

Generation of the phenoxyl radical (126) at 650°C was of particular mechanistic interest because (126) can abstract a hydrogen atom *via* the 7-membered transition state, as before, or from the *o*-methyl group[97b], to generate a benzyl radical. Thus, a trace of the ester (127) was detected by g.c./m.s., *m/z* 166. However, the ^{1}H n.m.r. spectrum of the isolated product indicated a methyl signal at δ_H 2.27 and a methylene signal at δ_H 5.25, consistent with the formation of the phthalide derivative (128, 20%), as the major product.



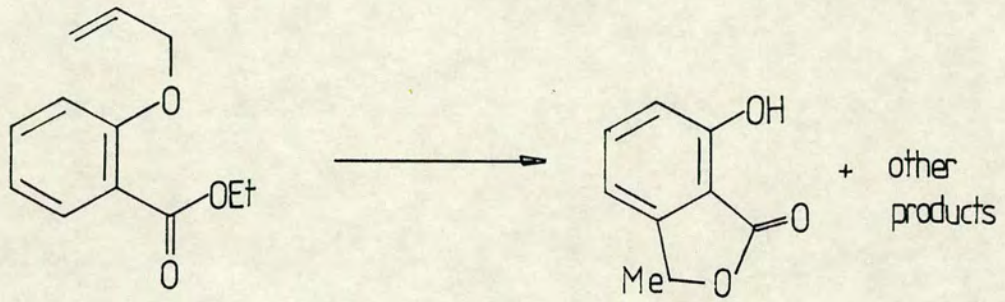
SCHEME 57

In the benzamide system, the possibility of fragmentation *via* a 3-membered spiro-intermediate was considered (Scheme 52). Similarly, the failure to detect any *o*-cresol or 2,2'-dihydroxybibenzyl suggests that fragmentation *via* a 4-membered spiro-intermediate (Scheme 58) also does not occur in the ester system.



SCHEME 58

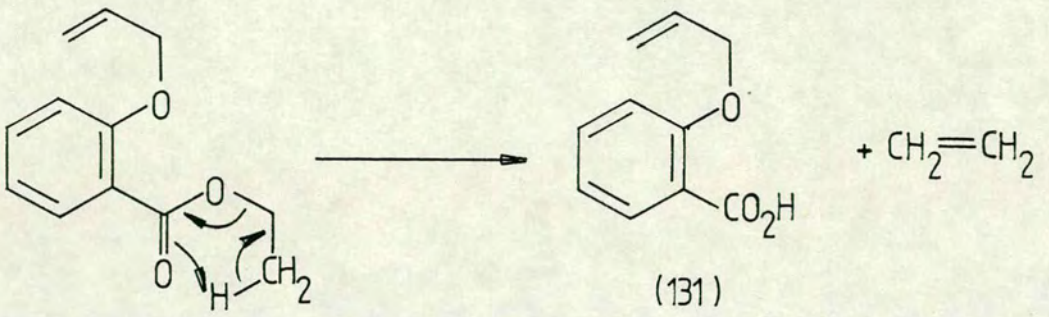
Similarly, fragmentation was not observed in the pyrolysis of ethyl 2-allyloxybenzoate (129) at 650°C. Instead, two products, one phenolic and one acidic, were isolated. The ^1H n.m.r. spectrum of the former compound, shows the characteristic quartet at δ_H 5.56 and doublet at δ_H 1.63, which indicates formation of the expected cyclised product (130, Scheme 59). However,



(129) (130)

SCHEME 59

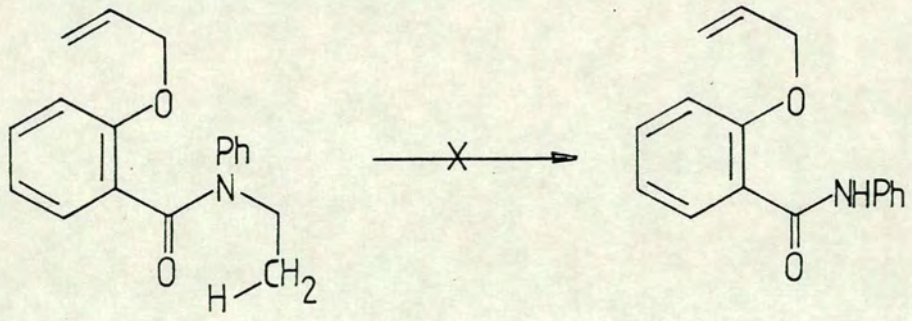
the major product was identified by mixed melting point, as 2-allyloxybenzoic acid (131), obtained by *cis*-elimination[62] of the ethyl ester (Scheme 60).



(131)

SCHEME 60

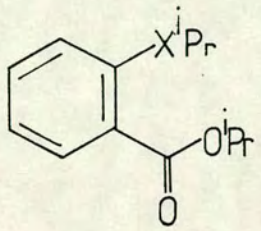
Similarly, the corresponding benzamide system (132) should undergo *cis*-elimination[62,98], with formation of (133) (Scheme 61), which is stable at furnace temperatures below 700°C [see Section 2B, (118)]. However no allyl groups were apparent from the ^{1}H n.m.r. spectrum of the crude pyrolysate, and therefore this process is not observed in this system.



(132) (133)

SCHEME 61

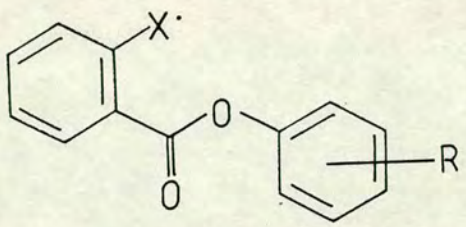
Finally, hydrogen transfer from a tertiary carbon centre was investigated by pyrolysis of the ester system (134) at 750°C. However, in each case, neither the cyclisation product or the product of *cis*-elimination were observed, and therefore the higher furnace temperature, required for radical generation, may promote alternative fragmentation and/or polymerisation.



(134; X= O, S)

Investigation of the amide and ester systems has highlighted some interesting mechanistic points, however it was hoped that the generation of radical systems, without available alkyl hydrogen atoms, would produce other types of cyclised products. These studies are discussed in the following sections.

D The Generation and Cyclisation of (2-Aryloxycarbonyl)phenoxyl and (2-Aryloxycarbonyl)thiophenoxyl Radicals (135)



(135; X=O, S)

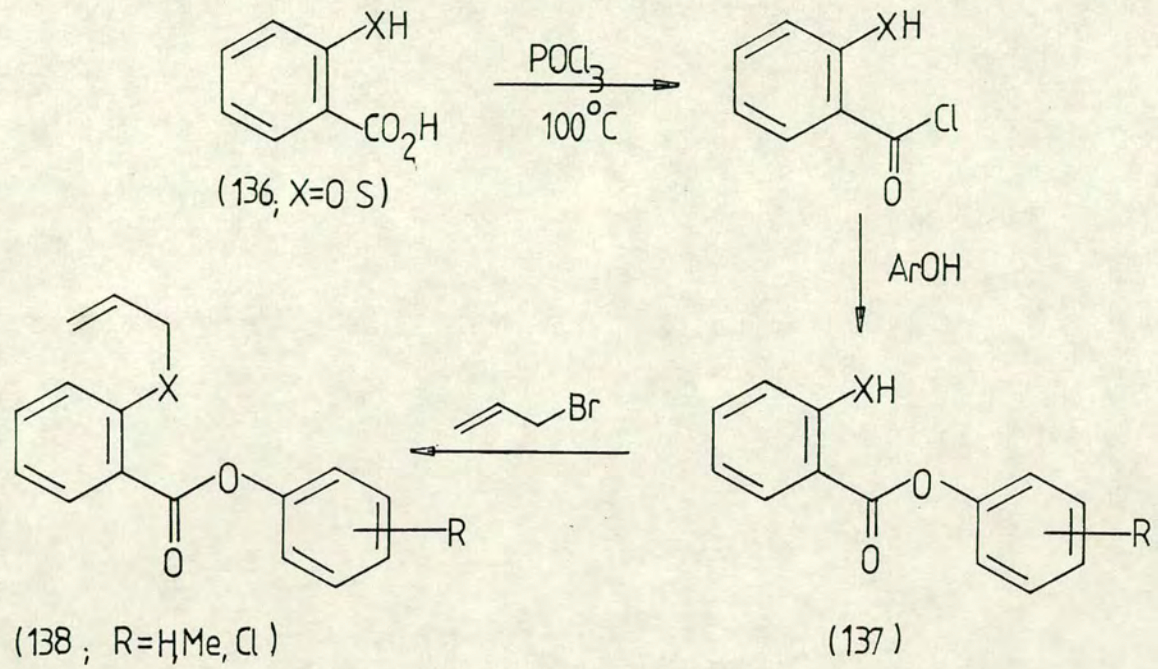
1. Preparation of radical precursors

The required radical (135) was generated from the *O*-allyl, *S*-allyl or *S*-isopropyl derivative, as appropriate. These compounds were prepared by one of two general methods.

(i) Method I

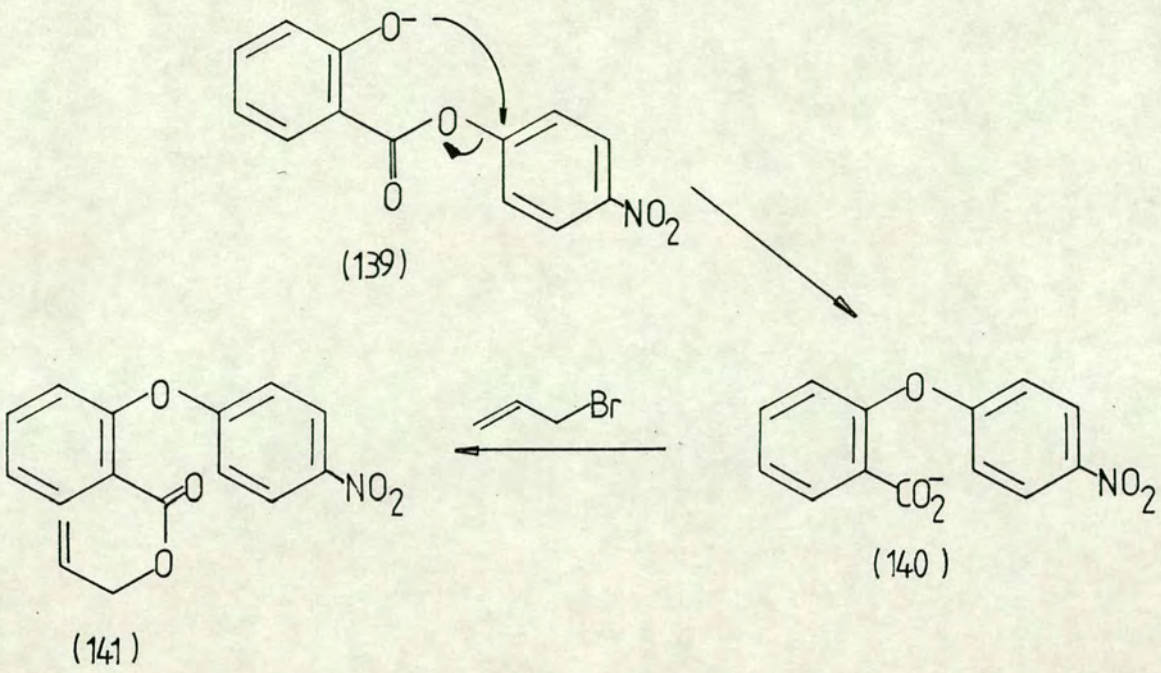
This involves reaction of the appropriate acid (136) with phosphoryl chloride, to generate the acid chloride, which is converted to the required phenyl ester (137) *"in situ"*, followed by alkylation under basic conditions (Scheme 62).

Commonly, yields of 30-60% have been obtained at the esterification stage, depending on the ease of isolation of (137), whereas the alkylation step proceeds quantitatively in all cases. Thus, the overall yield of compounds prepared by this method is shown in Section D.1.(iii), Table 1.



SCHEME 62

However, this route has proved unsuitable for the cases in which (138) is substituted in the *ortho* or *para* position, with a strongly electron-withdrawing group (eg $R=NO_2$, CN). This is because the phenoxyl anion (139), formed during the alkylation step, can undergo Smiles rearrangement[99] to the carboxylate anion (140), which is subsequently alkylated (Scheme 63). The ^{13}C n.m.r. spectrum of the rearranged product (141) shows an sp^3 methylene signal, characteristically at δ_C 65.00, and thus (141) can be distinguished from the desired phenyl ester system (138), where the corresponding signal appears at δ_C 70.00.

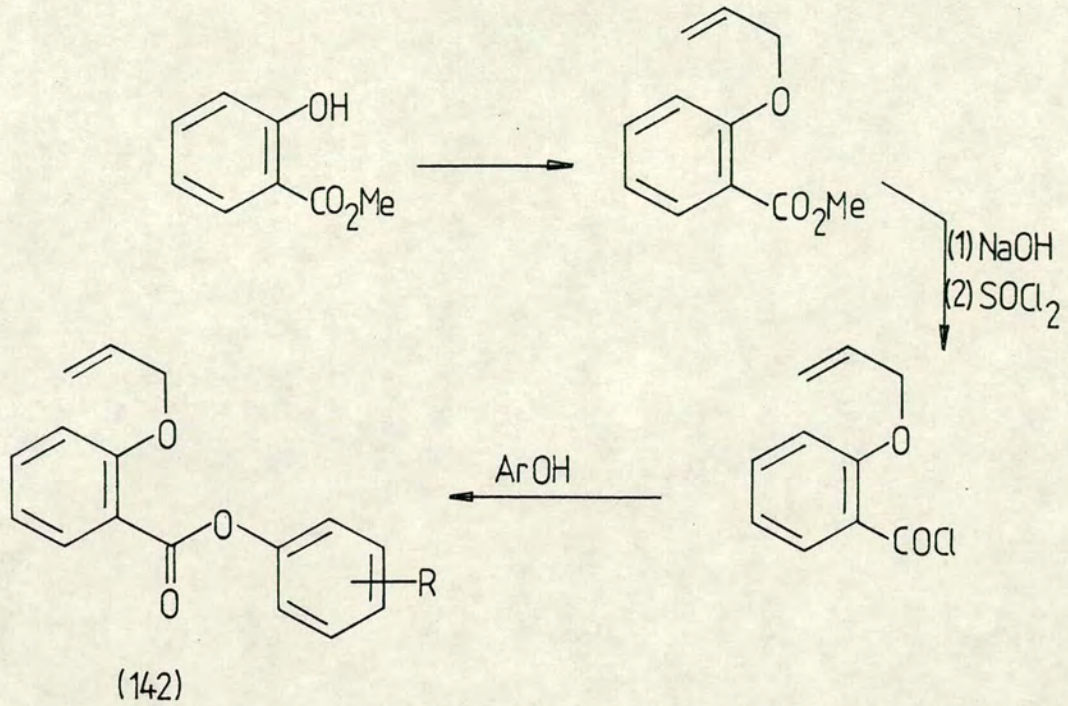


SCHEME 63

Therefore another method has been developed, wherein alkylation occurs before esterification.

(ii) Method II

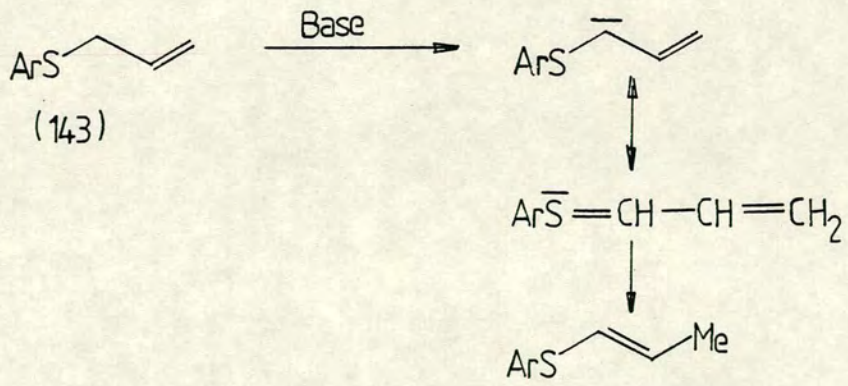
This can be applied to the preparation of a wide range of substituted *O*-allyl compounds (142) (R=H, Me, Cl, OMe, NO_2, CN) and involves the standard *O*-alkylation of methyl salicylate, followed by basic hydrolysis of the ester linkage to give the acid, which is then converted to the acid chloride and hence coupled with the required phenol (Scheme 64). Notably, the final step proceeds most efficiently (>80% yield), when catalysed by the hypernucleophilic reagent 4-dimethylaminopyridine (4-DMAP), which is widely used to effect acylation of sterically-hindered secondary and tertiary alcohols and phenols[100].



(142)

SCHEME 64

However, this route is unsuitable for the preparation of *S*-allyl derivatives (143), because the basic conditions employed for the ester hydrolysis can also generate a resonance stabilised carbanion which can isomerise to the propenyl sulphide[101] (144, Scheme 65). This product is



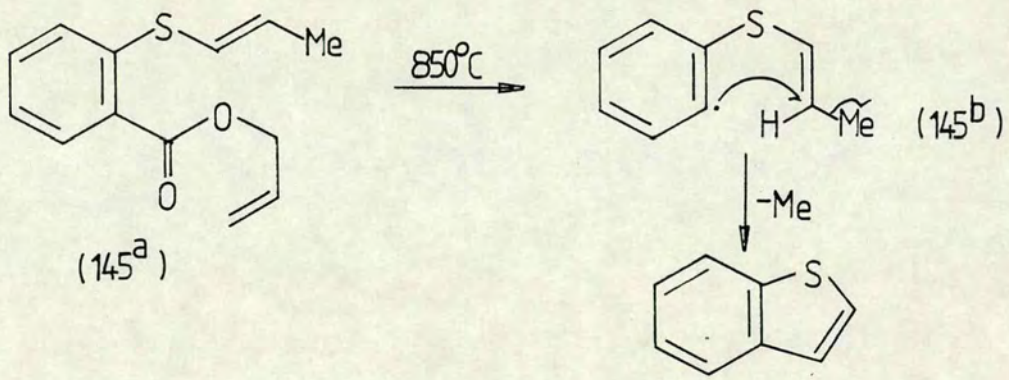
(143)

(144)

SCHEME 65

easily identified by its ^{1}H n.m.r. spectrum, where the characteristic methyl signal appears as a doublet at δ_H 1.90. This rearrangement is not observed in the corresponding *O*-allyl compounds because oxygen cannot expand its valence shell and therefore is unable to contribute to the carbanion stabilisation.

Interestingly, *O*-alkylation of the rearranged product with allyl bromide gave (145^a), which yielded a small quantity of benzothiophene, on pyrolysis at 850°C, *via* generation of the phenyl radical[71] (145^b) (Scheme 66). Other pyrolysis reactions related to this type are discussed in Sections F and G.



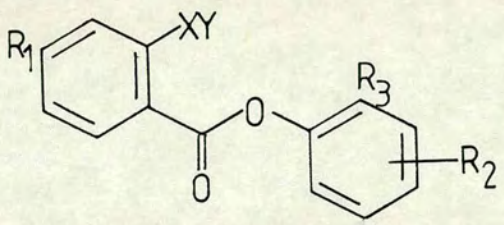
SCHEME 66

However, further attempts to prepare the required *S*-allylthiobenzoic acid by acid hydrolysis, also proved unsuccessful and therefore the iso-propyl group, which is stable under basic conditions, can be used in place of the allyl group as the radical generator[102], although

homolysis requires a furnace temperature of 750°C. Thus the required phenyl (2-isopropylthio)benzoate can be prepared from thiosalicylic acid by a method analogous to that depicted in Scheme 64.

(iii) Summary

Two methods have been developed, whereby the precursor system (146) can be prepared from either salicylic acid (where X=O) or thiosalicylic acid (where X=S), and the appropriately-substituted phenol. The yield of each compound (146) prepared by these methods is shown in Table 1.



(146)

TABLE 1

YIELDS OF ISOLATED PHENYL (2-ALLYLOXY)BENZOATES, PHENYL (2-ALLYLTHIO)BENZOATES AND PHENYL (2-ISOPROPYLTHIO)-BENZOATES

		PRECURSOR (146)				
X	Y	R_1	R_2	R_3	METHOD	OVERALL YIELD %
S	Allyl	H	H	H	I	53
	"	H	*o*-Me	H	I	28
	"	H	*m*-Me	H	I	16
	"	H	*p*-Me	H	I	32
	"	H	*o*-Cl	H	I	15
	"	H	*p*-Cl	H	I	28
	isopropyl	H	H	H	II	50[a]
	"	H	*o*-Cl	Cl	II	49[a]
O	Allyl	H	H	H	I	83[b]
	"	H	*o*-Me	H	I	66
	"	H	*m*-Me	H	I	37
	"	H	*p*-Me	H	I	38
	"	Me	H	H	I	86
	"	H	*o*-Cl	H	I	67
	"	H	*p*-Cl	H	I	58
	"	H	*o*-Cl	Cl	I	76
	"	H	*o*-OMe	H	I	52
	"	H	*p*-OMe	H	I	78
	"	H	*p*-NO_2	H	II	51[c]
	"	H	*p*-CN	H	II	64[c]

a from Thiosalicylic acid

b from Phenyl salicylate

c from Methyl salicylate

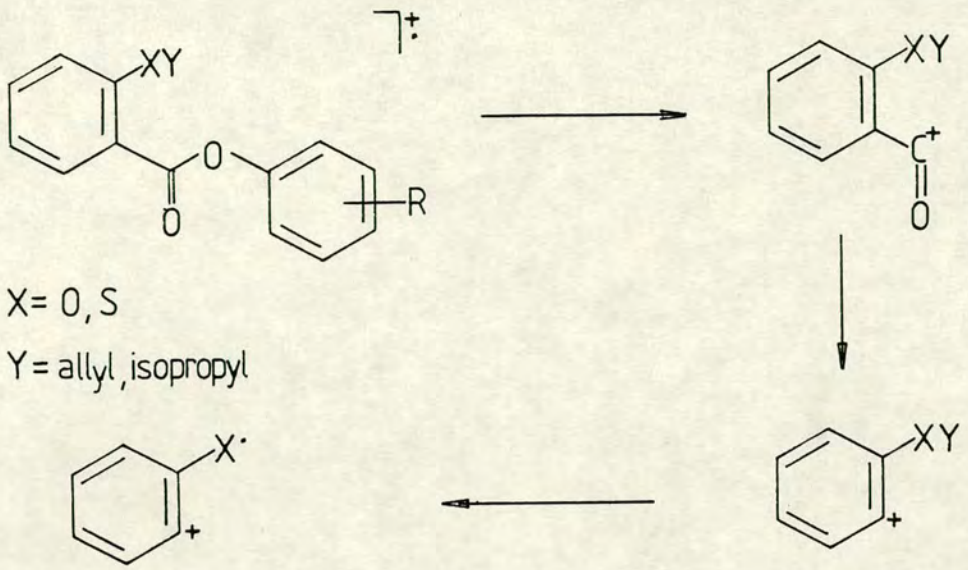
However the preparative method of choice is dependent upon the nature of the heteroatom (X) and of the ring substituents (R_2 and R_3). Thus Method I is inappropriate for electron-withdrawing aryl substituents (eg $R_2 = p$-NO_2, p-CN), because of competing Smiles rearrangement in the subsequent alkylation, whereas Method II fails for the *S*-allyl compound due to complications at the ester hydrolysis stage (Scheme 65), however the *S*-isopropyl compound can be prepared in this way, as an alternative precursor system.

2. Mass Spectra and Pyrolysis of Thiobenzoate and Oxybenzoate Systems

As expected from the study of the related alkyl benzoate systems, the mass spectra of the phenyl benzoate systems all show a similar fragmentation pattern, where α-cleavage of the ester producing a peak at M-OR, is followed by loss of carbon monoxide, although cleavage of the allyl or isopropyl group may then occur also (Scheme 67).

The pyrolysis of phenyl 2-allylthiobenzoate (146, X=S) at 650°C (10^{-3} Torr), produced a remarkably high yield of dibenzothiophene (88%), which was scraped from the cold trap and thus identified by melting point correlation.

A trace of phenol, identified by g.c./m.s., was the only other detectable product, and this can easily be removed by base extraction. Therefore this reaction could be developed as a preparative route to the dibenzothiophene system.



SCHEME 67

As detailed in the Introduction (Section II.B.3) several f.v.p.-mediated radical cyclisations have already been developed as synthetic routes to heterocyclic systems[e.g.86,87]. However, this new reaction is perhaps the most efficient gas-phase free radical cyclisation yet discovered, and unlike many of the other procedures, chromatographic separation is not required, either for precursor preparation or product isolation.

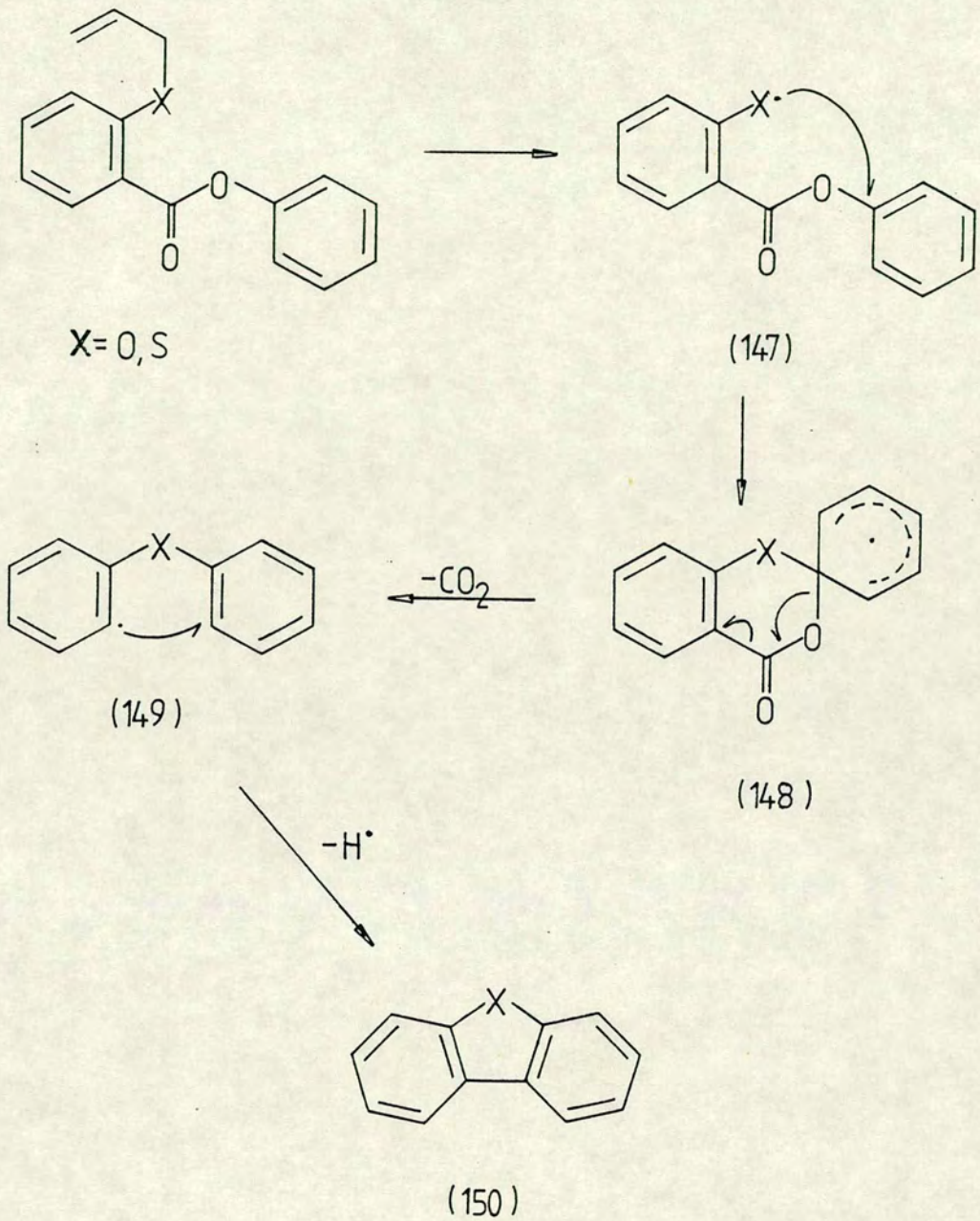
Therefore it was hoped to extend this reaction to the preparation of the dibenzofuran system. Thus pyrolysis of the related oxybenzoate compound (146, X=O), under the same conditions, produced dibenzofuran (62%) and a trace of phenol which were isolated and identified as above. Interestingly, no hydrogen abstraction products were

observed, unlike reaction of the related phenoxyl radical system[83] [104, Scheme 49, Introduction, Section II.B.3(iii)], however this is to be expected from the study of the (2-*N*-substituted carbamyl)phenoxyl radical system (118, 119, Section B).

Therefore before the synthetic scope of these reactions was developed further, the mechanism was rationalised, with reference to previous work carried out by Hutchison[87]. The trace of phenol can result from α-cleavage of the ester linkage, whereas formation of the cyclised product (150) can proceed by the mechanism proposed in Scheme 68.

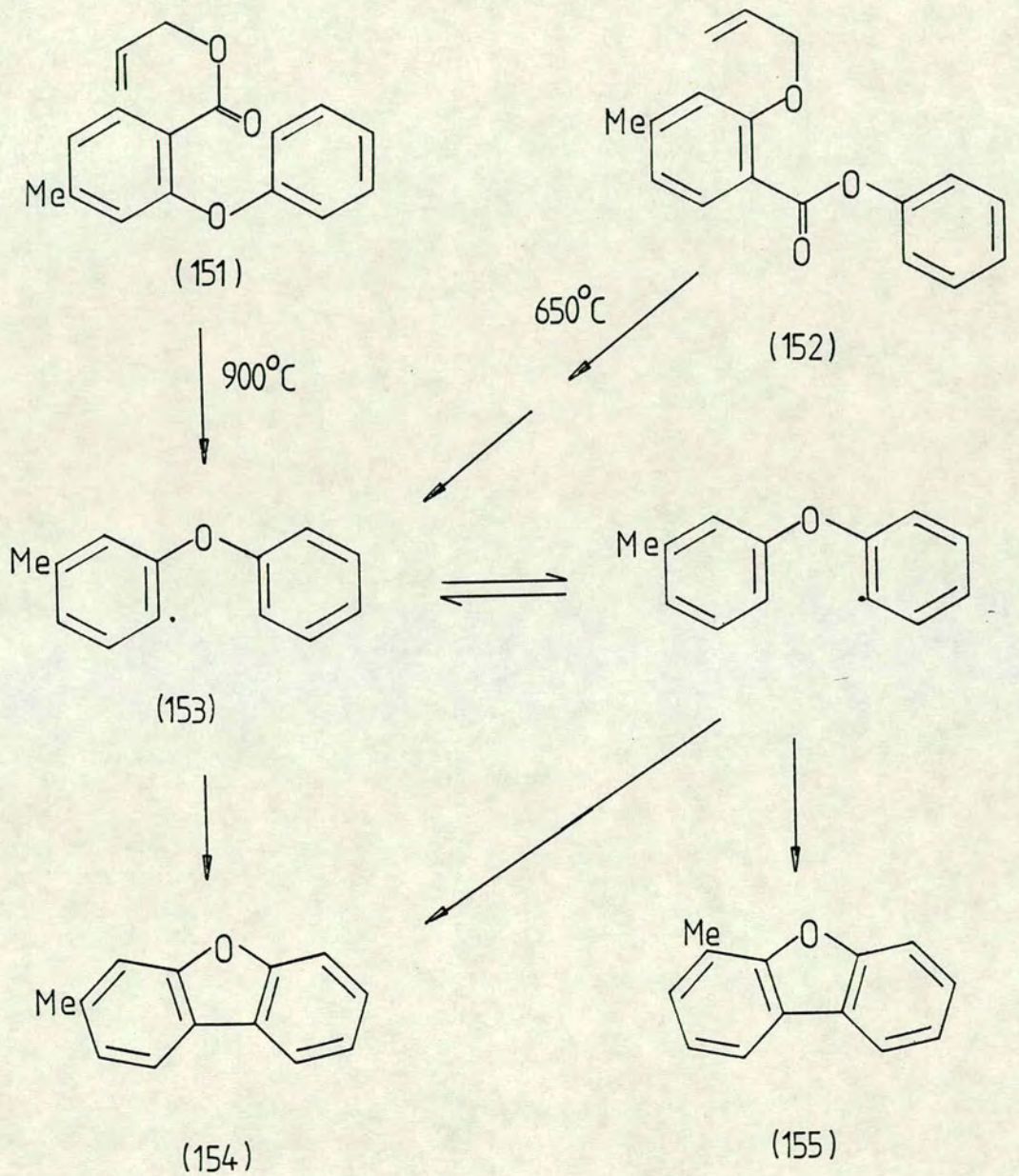
Thus generation of the phenoxyl (or thiophenoxyl) radical (147) is followed by cyclisation to the spirodienyl intermediate (148), which can open in the opposite sense to lose carbondioxide and hence generate the phenyl radical (149) which then cyclises directly. Thus the final step in this reaction is analogous to the solution-phase Pschorr reaction [Introduction, Section 2.A(v)].

Previous work[87] has shown that phenyl radicals of this type (149), generated directly from the appropriate allyl ester at 900°C, can also cyclise in this way. Furthermore, these radicals can abstract a hydrogen atom from the adjacent aryl ring, thus setting up an equilibrium. Moreover, when a substituent was placed on the same ring as the generated radical (151, Scheme 69) the formation of a 3:1 mixture of (154) and (155) respectively, showed that the radical system was fully equilibrated. Therefore, a similarly-substituted phenoxyl radical (152) was generated, and produced



SCHEME 68

the same distribution of products, thus indicating that cyclisation in these systems also proceeds *via* the phenyl radical (153, Scheme 69).

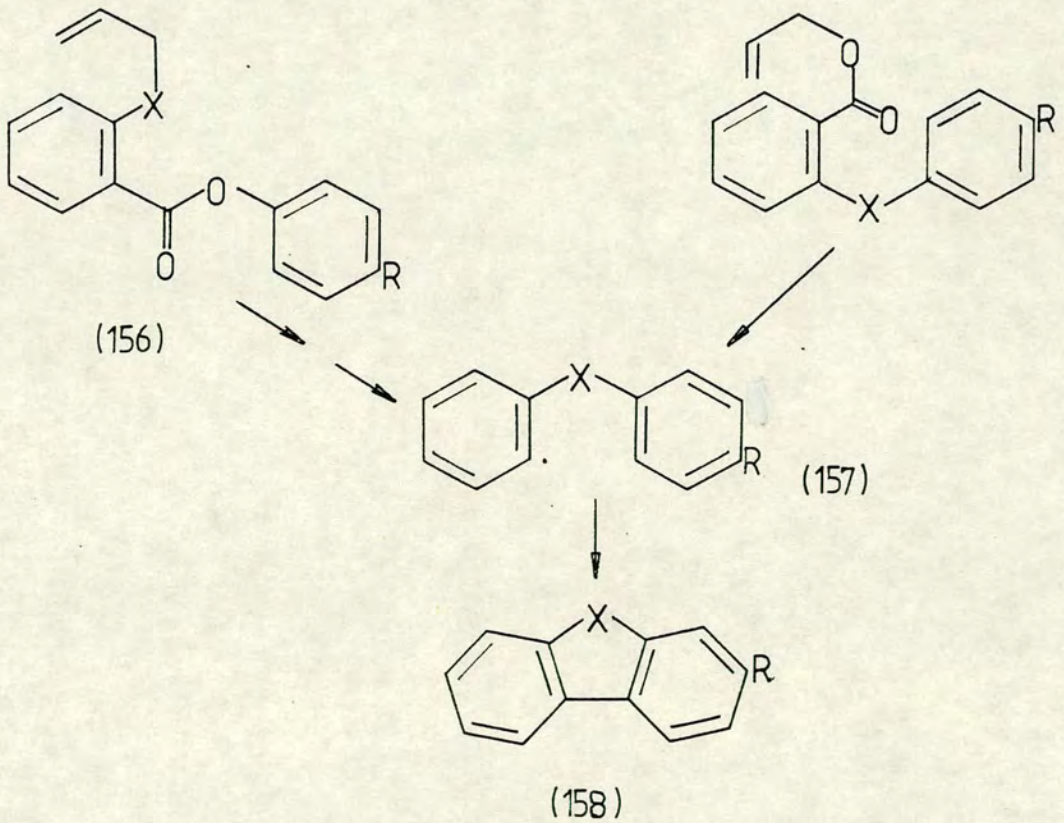


SCHEME 69

However, this equilibration can affect the synthetic viability of these reactions because in some cases the substitution pattern cannot be specifically designed. Therefore investigation of the phenoxyl-type radicals (152), has concentrated on systems that are substituted in the other ring.

(i) *para*-Substituted precursors

Pyrolysis of *p*-substituted precursors (156, X=O, S) at 650°C, can proceed via the mechanism proposed in Scheme 68, to give 2-substituted dibenzofuran (158, X=O) or 2-substituted dibenzothiophene (158, X=S) (Scheme 70). The



SCHEME 70

reaction proceeds irrespective of the electronic nature of the substituent, and thus is suitable for alkyl groups (eg R=Me), halogens (eg R=Cl), electron-donating groups (eg R=OMe) and electron-withdrawing substituents (eg R=CN, NO_2). Furthermore, the only significant side product is a trace of the phenol (ArOH), and this can be easily removed by base extraction.

The 2-substituted product (158), X=O,S) can also be obtained in lower yield, where the phenyl radical (157) is generated directly at 900°C[87] (Scheme 70), although some functional groups (eg -OMe) are unstable under these conditions, and column chromatography is required for product isolation. Therefore the new method is a more efficient preparative route.

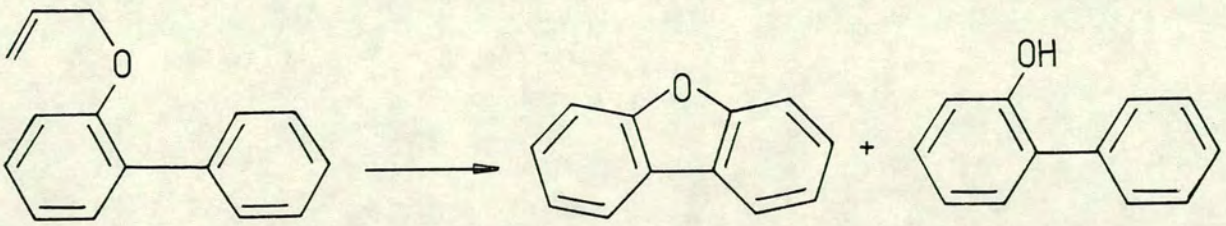
Of course, dibenzothiophenes and dibenzofurans, can also be prepared by a variety of other routes, such as via the Pschorr reaction[44,45], although the most widely used involve diphenyl ethers,[e.g.103,104,105] or biphenyls[e.g.106,107] However, this new route is more general and can be used to prepare a wide range of 2-substituted systems, with yields consistently above 70%, in effectively two steps from the appropriate phenol. The yields of pure, isolated products, obtained by the pyrolysis step, are shown in Table 2.

TABLE 2

Yields of Isolated and Purified 2-Substituted Dibenzofuran and Dibenzothiophene Derivatives

PRECURSOR (156)			PRODUCT (158)
X	Y	R	% YIELD
S	allyl	H	88
	"	Me	90
	"	Cl	92
	^{i}Pr	H	73
O	allyl	H	62
	"	Me	70
	"	Cl	75
	"	OMe	91
	"	CN	73
	"	NO_2	90

Interestingly, dibenzofuran can also be obtained in 75% yield by the pyrolysis of 2-allyloxybiphenyl (159) at 650°C (Scheme 71). However, 2-hydroxybiphenyl (19%) is also formed by a competing hydrogen abstraction reaction, but this can easily be removed by base extraction.



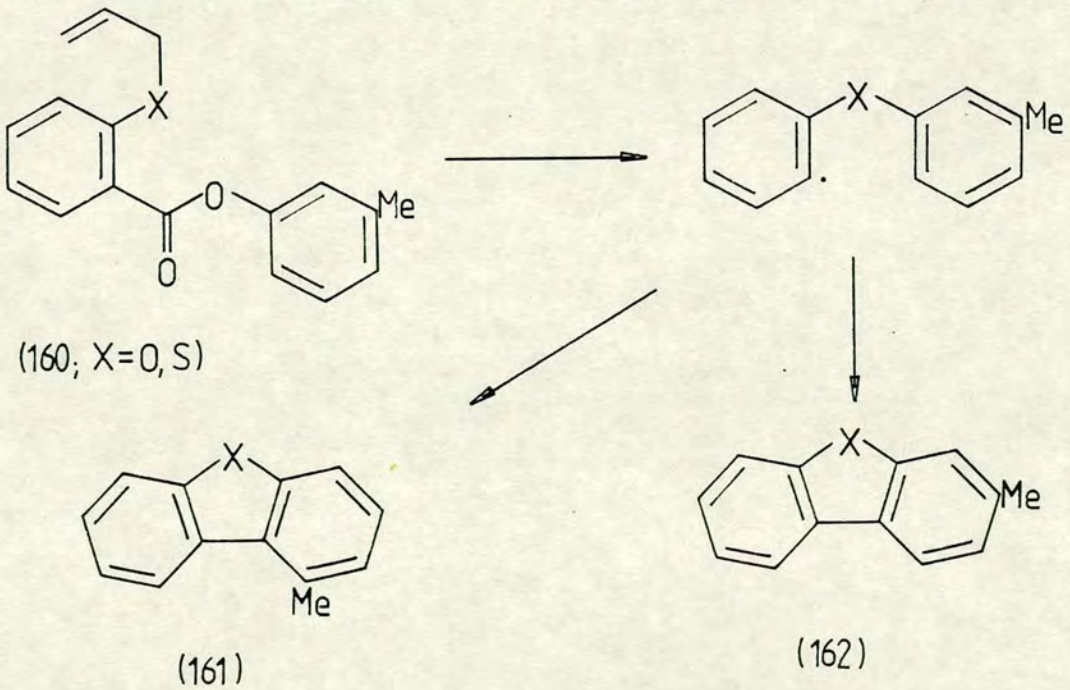
(159)

SCHEME 71

The precursor system (159) can be prepared quantitatively by *O*-alkylation of 2-hydroxybiphenyl under the standard conditions used for the benzoate systems. Therefore the synthetic viability of this route could be developed further, if the appropriately substituted biphenyl systems could be prepared. In fact this system can be obtained from arylboronic acids[108], and so this procedure could be incorporated into a new synthetic route to dibenzofurans and dibenzothiophenes.

(ii) *meta*-Substituted precursors

Pyrolysis of the *m*-substituted precursor system (160) was expected to give a mixture of 1- and 3-methyl substituted compounds (Scheme 72), although some selectivity in the cyclisation site was anticipated, thus favouring the formation of one isomer.

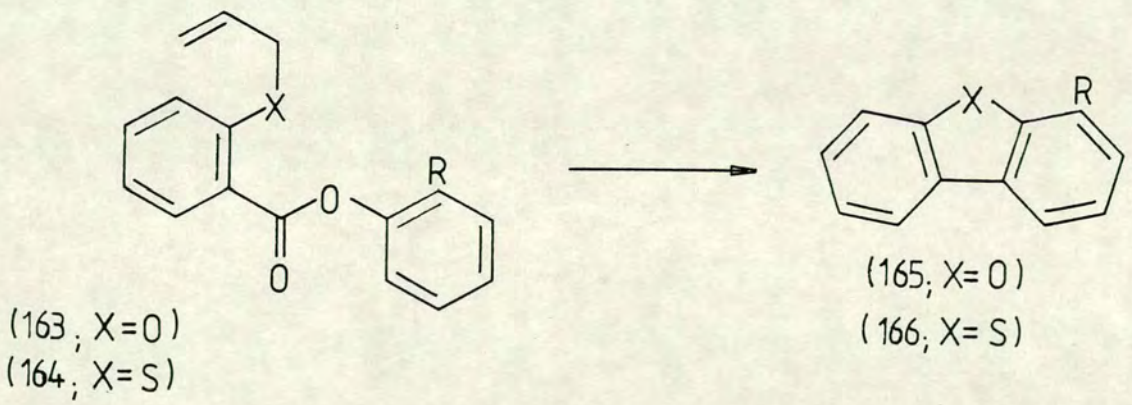


SCHEME 72

In the event, the pyrolysates of (160,X=O) and (160, X=S) were analysed qualitatively by g.c./m.s. and ^{1}H n.m.r. spectroscopy to reveal, in each case, an approximately 1:1 mixture of (161) and (162), and a trace of *m*-cresol as the only products. This lack of selectivity is also observed, where the phenyl radical is generated directly[87]. The two isomers can be distinguished by ^{1}H n.m.r. spectroscopy, because the methyl signal of (161) appears at higher frequency than that of (162) due to the deshielding influence of the unsubstituted aromatic ring. Unfortunately, attempts to separate this isomeric mixture have proved unsuccessful[87]. Therefore the synthetic viability of this reaction is limited by lack of selectivity, however this process may be applicable to cases in which the isomeric mixture can be separated.

(iii) *ortho*-Substituted precursors

It was expected that pyrolysis of these derivatives (163) and (164) would provide a route to the 4-substituted products (165) and (166) (Scheme 73).



(163; X=O)
(164; X=S)

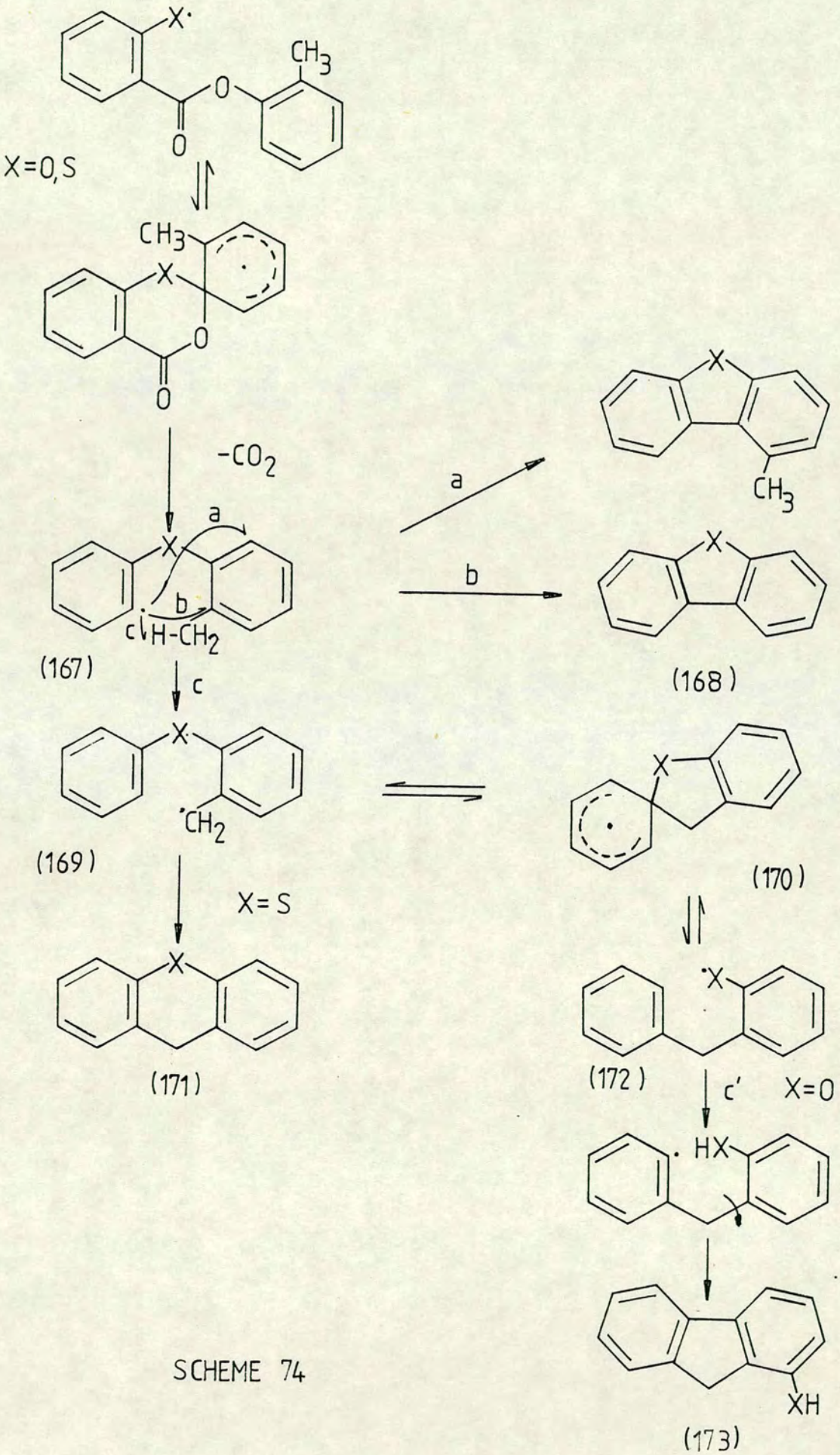
(165; X=O)
(166; X=S)

SCHEME 73

Pyrolysis of the methyl derivatives (163) and (164) at 650°C, each produced the expected product (165; R=Me, 31%) and (166, R=Me; 39%), respectively, together with small amounts of *o*-cresol and the unsubstituted cyclised products (165 and 166; R=H). These compounds were easily separated by column chromatography. 1-Hydroxyfluorene was identified as a minor product from the pyrolysate of (163), by ^{1}H n.m.r. spectroscopy, whereas a small signal at δ_H 4.06 suggests the formation of xanthene [authentic δ_H 4.05 (2H, s, CH_2)], but this is unlikely considering the results previously observed by McNab and Hutchison (discussed below), and therefore this signal may indicate the presence of some other unidentified minor product. However, thioxanthene can be produced from (164) (see Experimental Section).

Thus, *o*-cresol can result from the alternative cleavage of the precursor system, as observed in the *meta* and *para*-substituted analogues, and the mechanism proposed for the formation of the other compounds is outlined in Scheme 74.

Thus the initial radical can react as before, to generate the phenyl radical (167), which can then follow one of three competing pathways. Route a is the favoured pathway, and involves attack of the unsubstituted *ortho* site to give the expected product, whereas the competing *ipso* attack (Route b) results in ejection of the substituent and thus formation of (168) as a minor product. Ejection of an *ortho* substituent by an adjacent phenyl radical has previously been observed in solution[20] (Introduction, Scheme 20), and

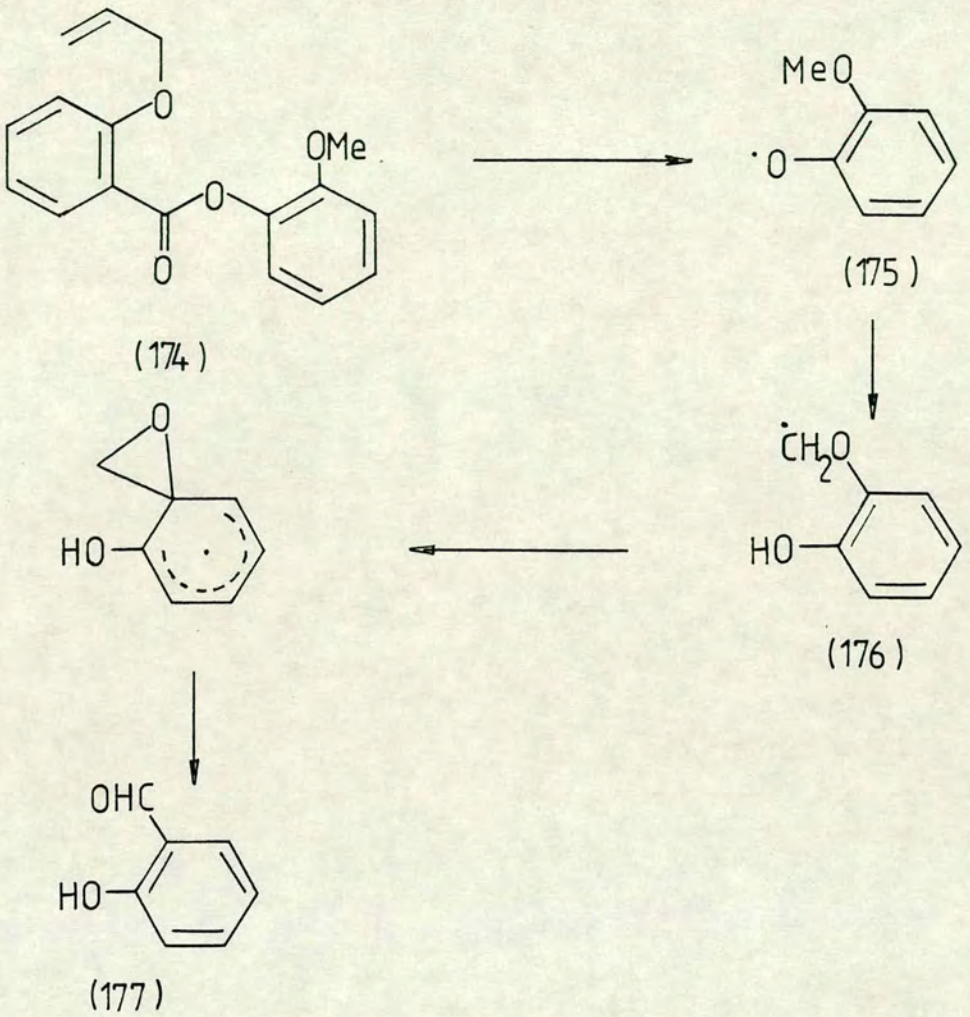


SCHEME 74

by conjugated iminyl radicals in the gas phase[92] (Introduction, Scheme 48).

On the other hand, (167) may abstract a hydrogen atom from the *o*-methyl group, (through a 7-membered transition state) to generate the benzyl radical (169) (Route c). Thus cyclisation via the spiro-intermediate (170) can result, and where X=S, thioxanthene (171) is produced. However, where X=O, the phenoxyl radical (172; X=O) can follow an alternative pathway involving hydrogen transfer and cyclisation to form 1-hydroxy-fluorene (173) (Route c^1). These findings are consistent with the observations of McNab and Hutchison[87], whereby the independent generation of both (169; X=O) and (172; X=O) each produced (173) as the major product, with only a negligible quantity of xanthene (171; X=O); whereas the generation of (169; X=S) and (172; X=S), failed to produce any of the rearranged product (173; X=S).

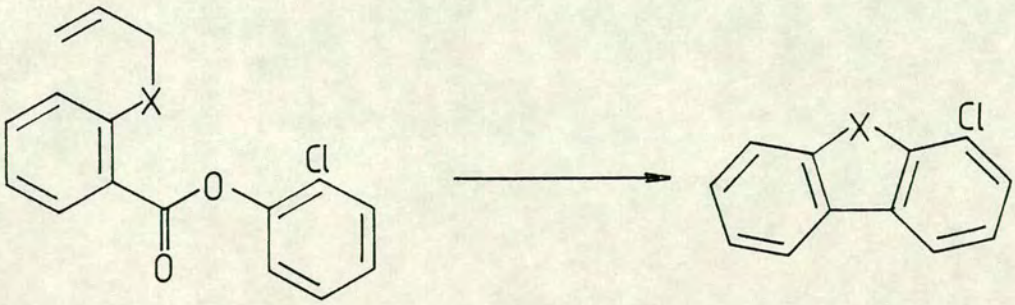
Investigation of the '*ortho*'-system was extended to the pyrolysis of 2-methoxyphenyl 2-allyloxybenzoate (174), at 650°C. Qualitative analysis, by g.c./m.s. and ^{1}H n.m.r. spectroscopy, indicates the formation of 4-methoxydibenzo-furan, and dibenzofuran as expected, together with a small quantity of salicylaldehyde (177) which may result from alternative cleavage of the ester linkage, by the mechanism outlined in Scheme 75. Thus the phenoxyl radical (175) can abstract a hydrogen atom from the *o*-methoxy group to generate the β-radical (176), which can then undergo a neophyl-type rearrangement[57] (see Introduction, Scheme 37).



SCHEME 75

These reactions are of mechanistic interest, however it was hoped that the preparative route to 4-substituted products could be improved by using presursors with non-hydrogen containing *ortho*-substituents, such as the *o*-chloro derivatives (178 and 179, Scheme 76).

Hence, pyrolysis of the allyloxy compound (178) at 650°C, gave the expected product (180, 22%) and a trace of dibenzofuran, detected by g.c. However pyrolysis of the thio analogue (179) at 650°C, produced the unsubstituted



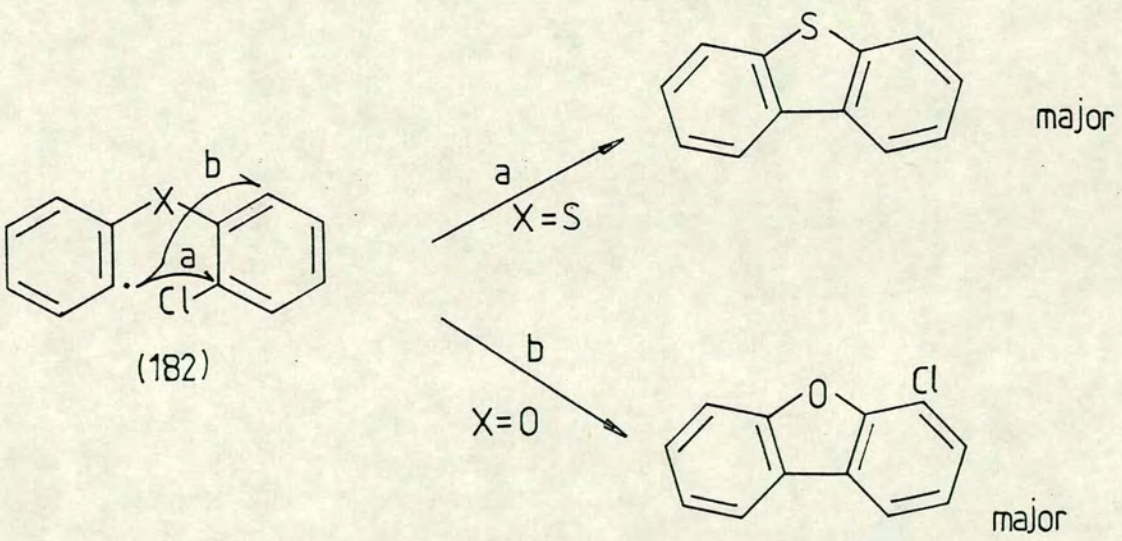
(178; X=O)
(179; X=S)

(180; X=O)
(181; X=S)

SCHEME 76

dibenzothiophene (23%) as the major product, together with the 4-chloro derivative (13%) and an unidentified product, detected by g.c., which could not be isolated by column chromatography (see Experimental Section).

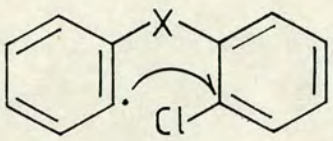
Thus generation of the phenyl radical (182) may proceed as before (Scheme 74), however unlike the previous systems the heteroatom (X), in this case, can determine the predominant site of attack of (182) (Scheme 77).



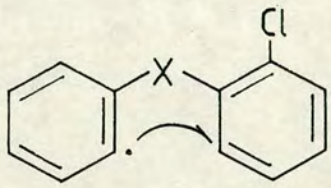
SCHEME 77

There is no obvious explanation for this observation, however the selectivity of each reaction may arise from geometrical and/or electronic effects inherent in this system.

Thus, if the configurations (183) and (184) are considered, then it can be seen that where X=O, the internuclear distance is considerably smaller than in the sulphur case, and so the transition state from (183; X=O)



(183)

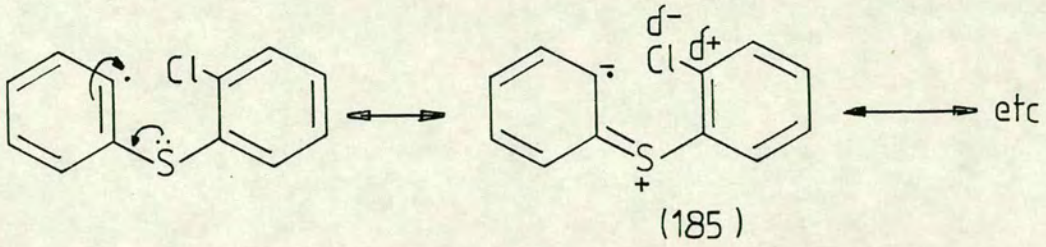


(184)

may be disfavoured due to steric hindrance. Therefore, in this case reaction occurs predominantly at the unsubstituted site (184).

Furthermore, the chlorine atom can exert a small negative inductive effect on the system and thus partially polarise the C-Cl bond (Scheme 78). Moreover, sulphur being a better electron donor than oxygen, can increase the nucleophilic nature of the phenyl radical, as shown by the canonical form (185) (Scheme 78). Therefore radical substitution can occur preferentially at the slightly more positive centre.

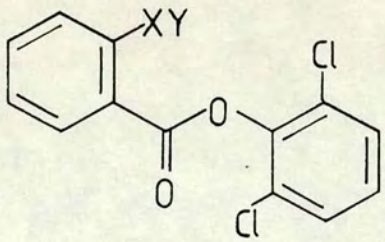
Nevertheless, qualitative analysis by g.c. has indicated that it is possible to obtain the 4-chloro product exclusively, in both systems, by pyrolysis of the appropriate



(185)

SCHEME 78

dichloro precursor, ie (186) or (187). Therefore this method could have some potential as a preparative route to the 4-chloro system.



(186; X = O, Y= allyl)

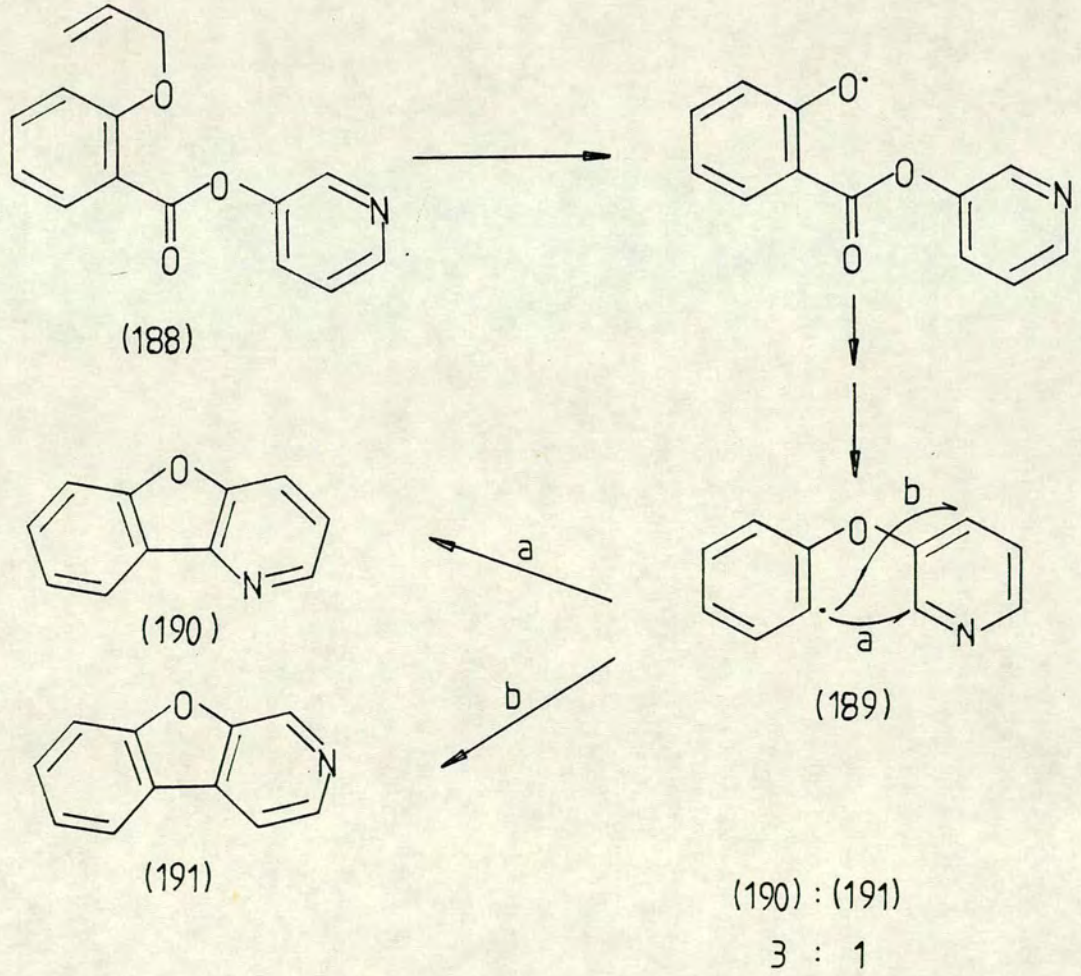
(187; X = S, Y= isopropyl)

3. <u>The Pyrolysis of Heterocyclic and Polynuclear Aromatic Systems</u>

It was hoped to extend the synthetic scope of the phenoxyl radical to the preparation of a range of fused heterocyclic and polynuclear aromatic systems. The precursor systems were synthesised by Method II described in Section D.1(ii), and the radicals were generated at

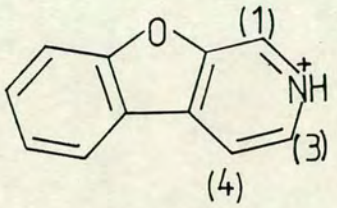
650°C (10^{-3} Torr).

Firstly, the 3-pyridyl system (188) was selected because it resembles the *m*-substituted benzoate system (Scheme 72) in its substitution pattern. Thus pyrolysis of (188) gave an isomeric mixture of the benzofuro-pyridine compounds (190) and (191) (Scheme 79), as expected. However a ^{13}C n.m.r. (D.E.P.T.) experiment has shown that, unlike the previous reaction, the radical (189) exhibits selectivity and the isomers are obtained in a ratio of 3:1.



SCHEME 79

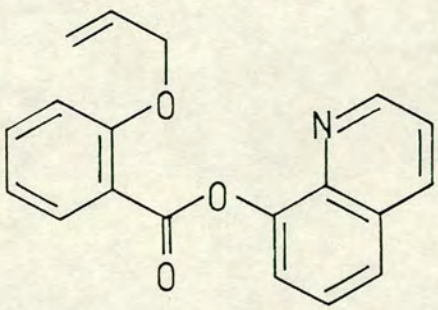
The picrate of the minor product was isolated from the isomeric mixture by recrystallisation and identified as (192) by its ^1H n.m.r. spectrum which shows a singlet at δ_H 9.63, corresponding to the highly deshielded proton (1), and a doublet of doublets at δ_H 8.90 and δ_H 8.30, which exhibit a characteristic coupling constant[109a] of $^3J_{3,4}$=6Hz, corresponding to protons (3) and (4). Thus



(192)

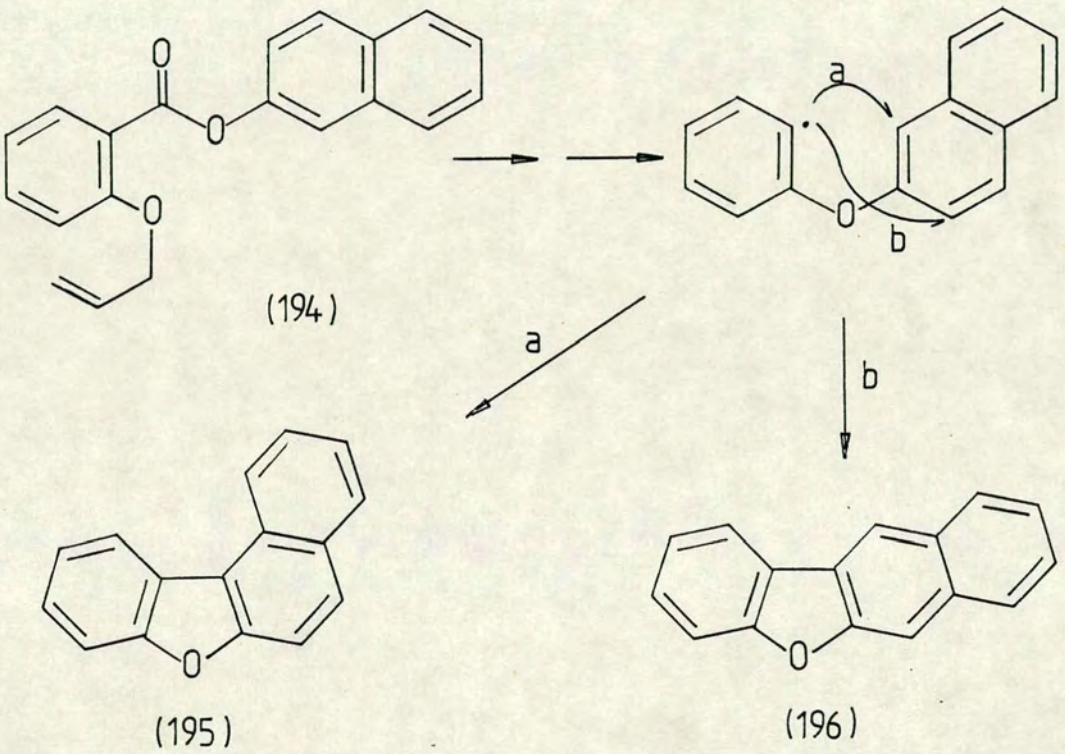
formation of the major isomer (190) involves attack of the pyridine ring at C-2 (Route a), and this is the favoured site of radical substitution in the pyridine system[109].

The 8-quinolinyl system (193) was also successfully prepared, however on pyrolysis, cyclisation did not occur as 8-hydroxyquinoline (34%) was obtained as the major product. Therefore this indicates that in this system, α-cleavage of the ester linkage is favoured over homolysis of the *o*-allyl bond.



(193)

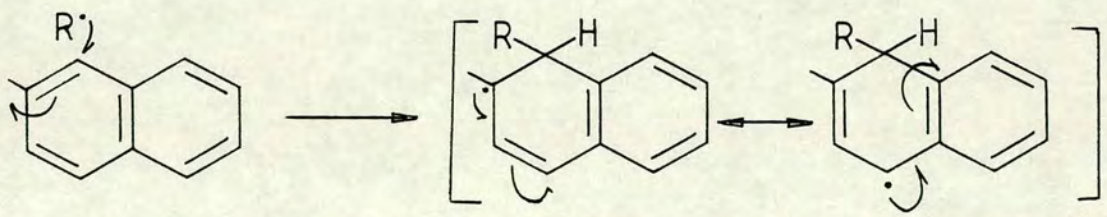
However, pyrolysis of the related β-naphthyl system (194) gave only a trace of β-naphthol, detected by g.c., whereas a ^{13}C n.m.r. (D.E.P.T.) experiment has indicated that the expected isomers (195) and (196), are obtained in a 4:1 ratio, as the major products (Scheme 80).



SCHEME 80

Preparative pyrolysis of this system gave the isomeric mixture in a combined yield of 91%, and the minor isomer was isolated by recrystallisation and thus identified as β-Brazan (196, 19%). Due to its low melting point the major isomer could not be isolated this way, which is consistent with the formation of γ-Brazan (195) (lit.[110] m.p. 42-45°C). Therefore, this indicates that radical substitution at the α-position of the naphthyl group (Route a) is favoured over β-attack. Intermolecular radical attack at the α- and β-positions of naphthalene gives similar regioselectivity[e.g.111] and this can be readily explained by considering the relative stabilities of the intermediate radicals formed.

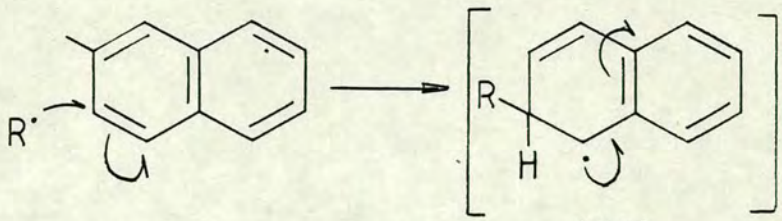
Thus α-attack can yield a species with two resonance forms (197) and (198), where the aromaticity of one ring is retained (Scheme 81). Whereas upon β-attack, the



(197) (198)

SCHEME 81

intermediate radical has only one canonical form (199), wherein the full resonance stabilisation of one benzene ring is retained (Scheme 82).

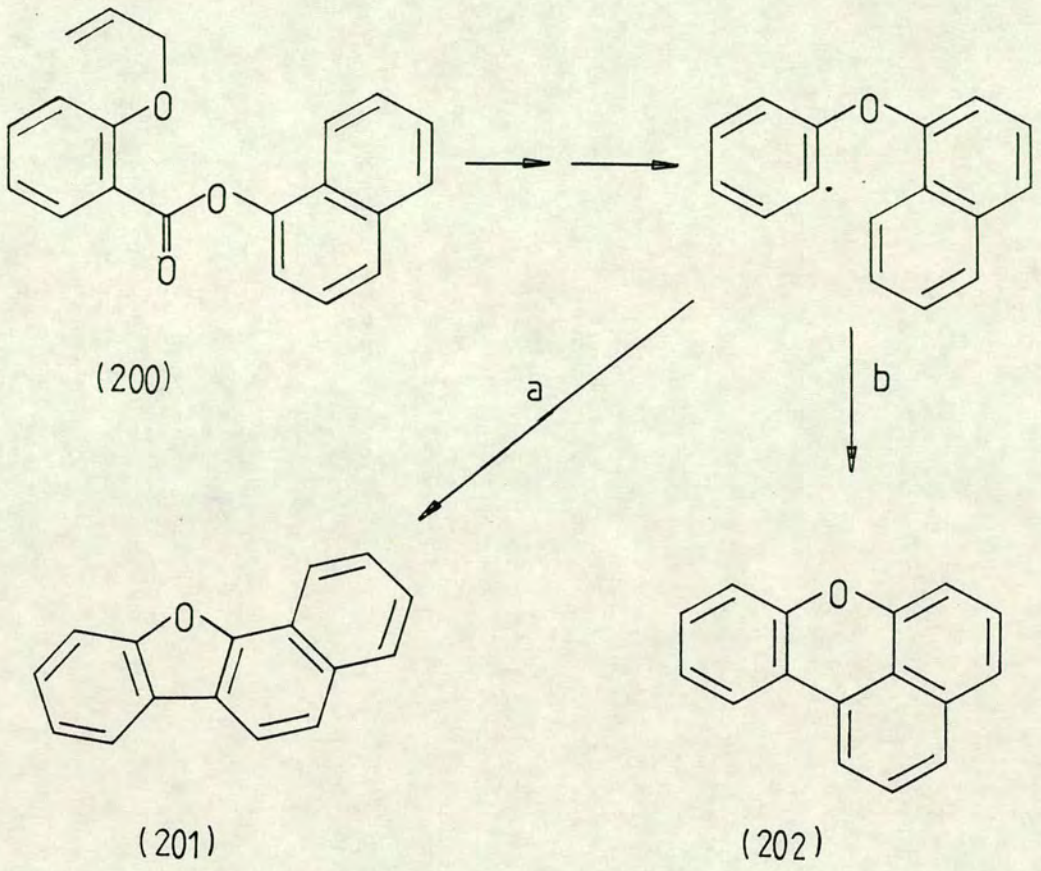


(199)

SCHEME 82

Pyrolysis of the related α-naphthyl system (200) produced a trace of α-naphthol, together with two major products, which were detected by g.c. However, these compounds could not be separated by either column chromatography or recrystallisation and thus have not been identified. Nevertheless, the ^{13}C n.m.r. (D.E.P.T.) spectrum of the mixture, taken after base extraction, shows the presence of twenty methine signals, which is consistent with the formation of the expected isomeric products (201) and (202) (Scheme 83).

The possible formation of (202) is an unusual result because six-membered ring-closure by this route is unprecedented. However, related aryl radical systems generated in solution, are known to undergo an analogous six-membered ring formation[46,52], provided that the radical centre and its site of attack are between 1.5Å and 2.5Å apart[20] (see Introduction, Section I.A(v)). Therefore it is not unlikely that such reactions could occur in the gas phase.



SCHEME 83

4. Summary

Through the study of (2-aryloxycarbonyl)phenoxyl and (2-aryloxycarbonyl)thiophenoxyl radicals, a new and efficient synthesis of dibenzofurans and dibenzothiophenes, from aryl salicylates, has been developed.

The radical precursors can be readily prepared from salicylates and phenols, but the key step involves a novel rearrangement-extrusion-cyclisation sequence of the radical to create the new 5-membered ring.

The pyrolysis conditions (650°C, 10^{-3} Torr) are compatible with the presence and electronic nature of a wide

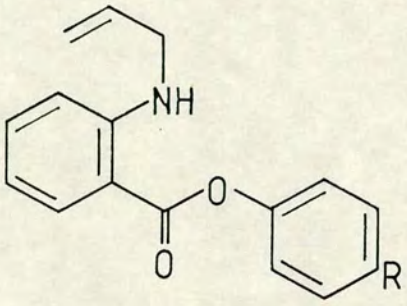
range of substituents on both rings. Yields of dibenzofuran and dibenzothiophene derivatives are generally high, particularly for *para*-substituted aryl groups (Ar), which give the 2-substituted product. The only significant side product is a trace of the phenol (ArOH) which can be easily removed by base extraction.

Radical cyclisations on *ortho*-substituted aryl rings are subject to complicating factors, but nevertheless 4-substituted products can generally be isolated in yields of 30-40%, after chromatography. Moreover, where the aryl ring contains a *meta*-methyl group, a statistical mixture of 1- and 3-substituted products is obtained. However where the reaction has been successfully applied to the preparation of certain fused heterocyclic and poly-nuclear aromatic systems (ie which are effectively *meta*-substituted), some selectivity has been observed. Finally, there is some evidence to suggest that with appropriate precursor design, 6-membered ring formation may also be achieved, however further research is required in this area.

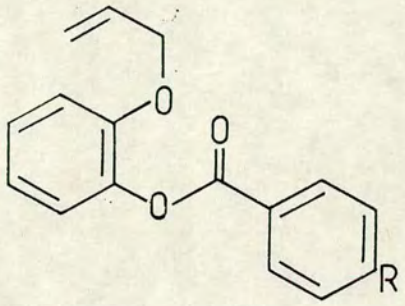
E Preparation and Pyrolysis of Other Systems Related to Aryl (2-allyoxy)benzoate

Three systems were investigated:

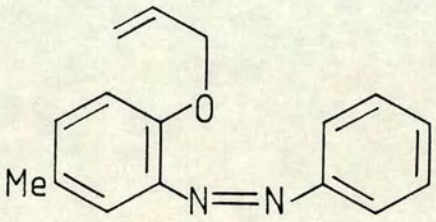
(1) Aryl (2-allylamino)benzoate (203) and related compounds; (2) (2-allyloxy)benzoates (204), and (3) (2-allyloxy-5-methyl)azobenzene (205).



(203; R=H,Me)



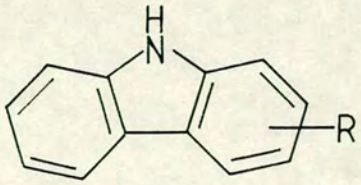
(204; R=H,Me)



(205)

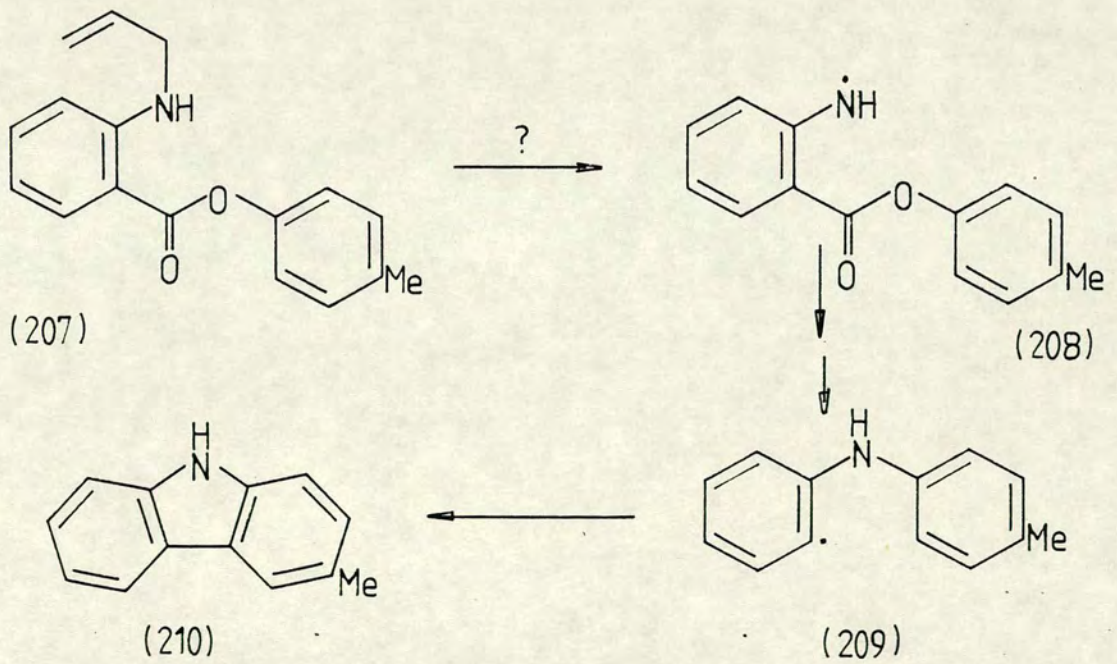
1. Aryl (2-allylamino)benzoate and Related Systems

Having successfully used the indirect generation of phenyl radicals as a preparative route to substituted dibenzofurans, dibenzothiophenes and related systems (Section D), it was hoped to extend this method to the synthesis of carbazoles (206).



(206)

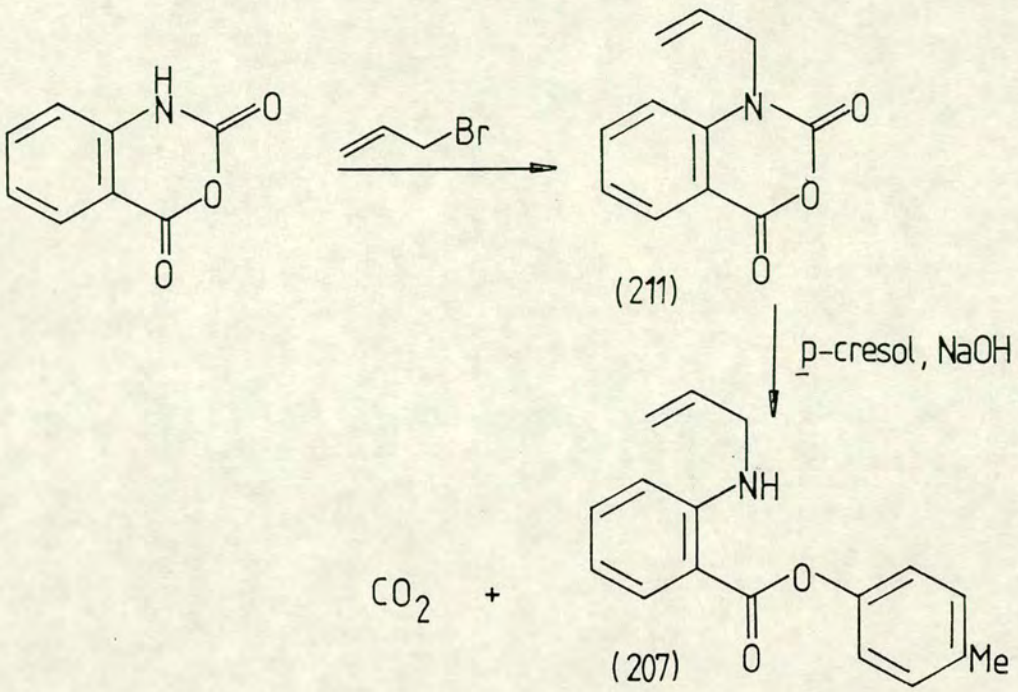
Thus, it was expected that pyrolysis of 4-methylphenyl (2-allylamino)benzoate (207) would generate the aminyl radical (208), which could rearrange with loss of CO_2 to the phenyl radical (209) and then cyclise to 2-methylcarbazole (210, Scheme 84).



(207) (208) (209) (210)

SCHEME 84

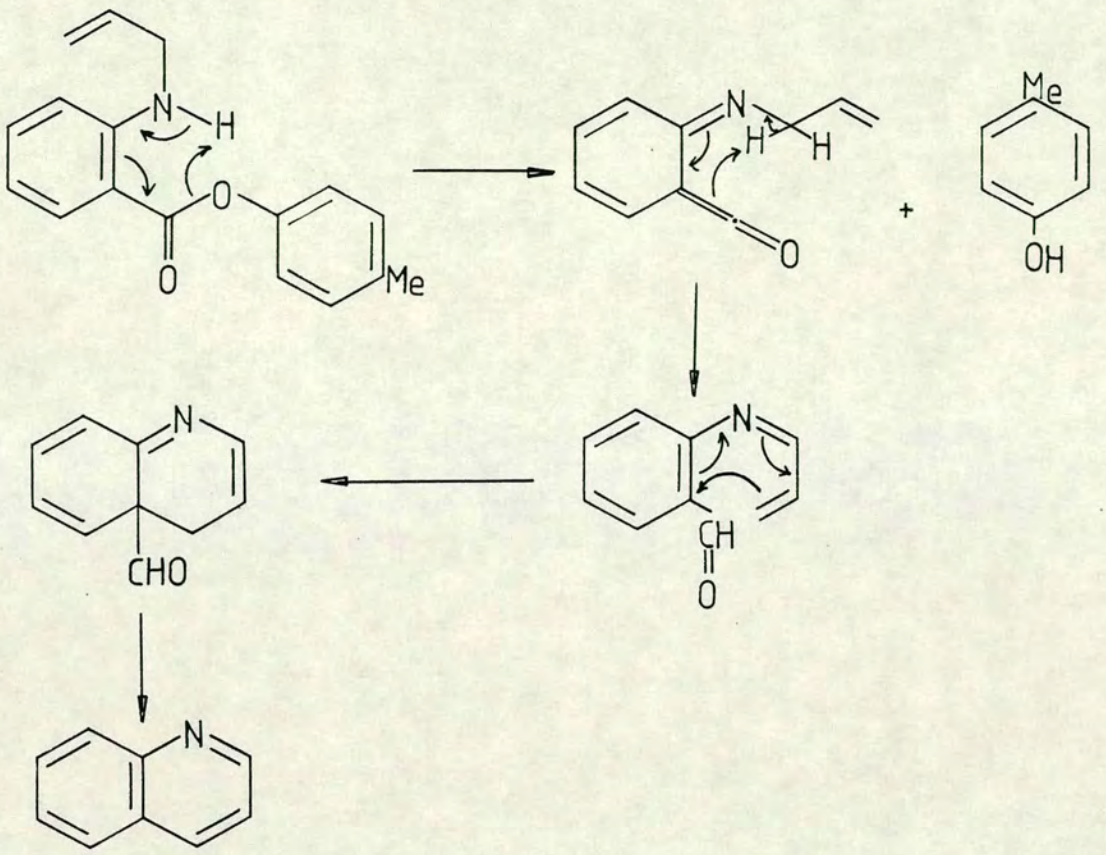
Hence, the precursor compound (207) was prepared by *N*-alkylation of isatoic anhydride, using allyl bromide under basic conditions to give (211), which was then reacted with *p*-cresol and sodium hydroxide[112] (Scheme 85).



SCHEME 85

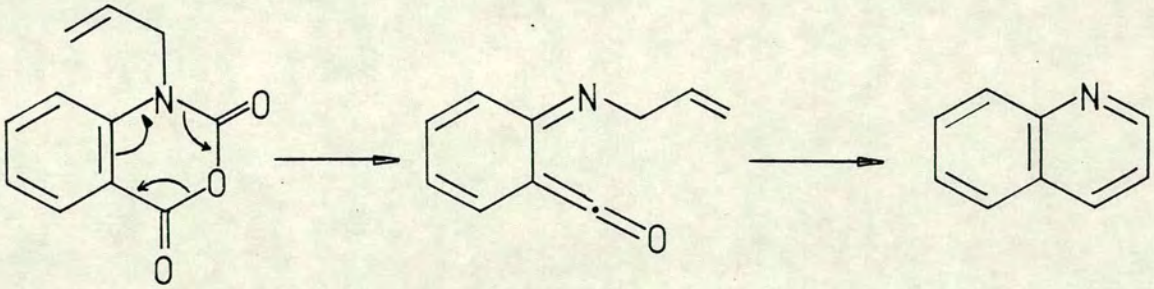
Isatoic anhydride is an ideal starting material because its structure provides protection of the amino group against dialkylation, required for the first step, and activation towards nucleophilic attack, required for the second.

However, pyrolysis of this compound (207) at 650°C gave *p*-cresol, as the major product, but no carbazoles were detected. Repeat pyrolysis at a higher temperature (850°C) again produced *p*-cresol, together with a small quantity of quinoline and thus formation of these compounds can result by the mechanism outlined in Scheme 86. This rearrangement has previously been observed by Boekelheide[113] on pyrolysis of similar compounds, and indeed *N*-allylisotoic anhydride (211) undergoes such a process, on pyrolysis at



SCHEME 86

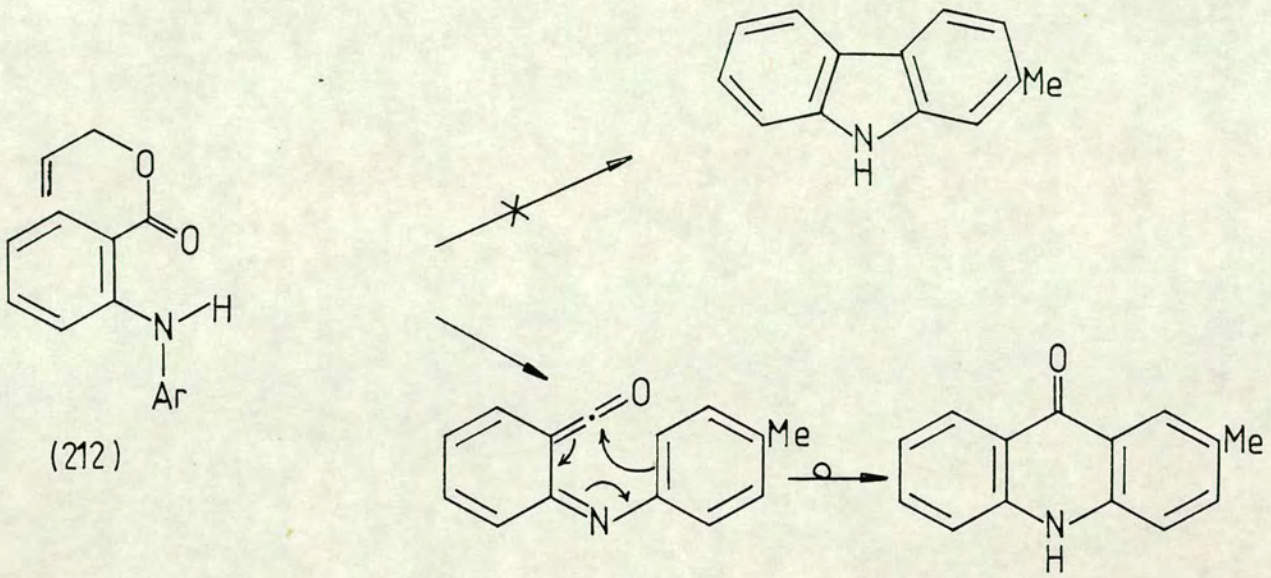
850°C, to give quinoline as the major product (Scheme 87). Thus high energy input is required for quinoline formation.



SCHEME 87

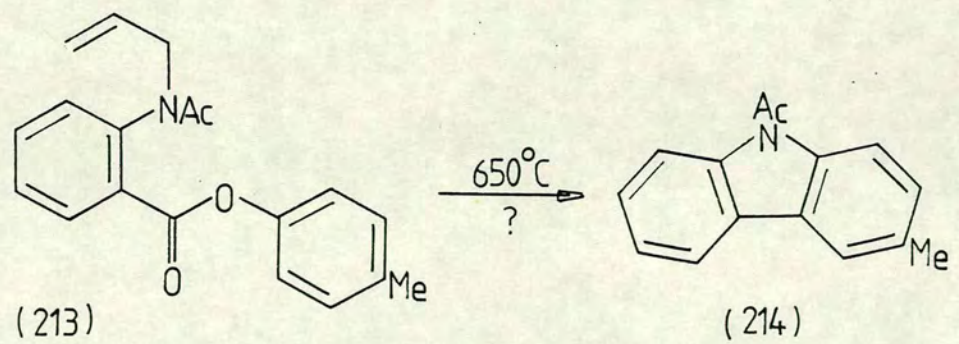
Similarly where Hutchison [87] attempted the synthesis of carbazole by direct generation of the phenyl radical, at 900°C, from allyl 2-(4-methylphenylamino)benzoate (212)

this rearrangement was also observed (Scheme 88).



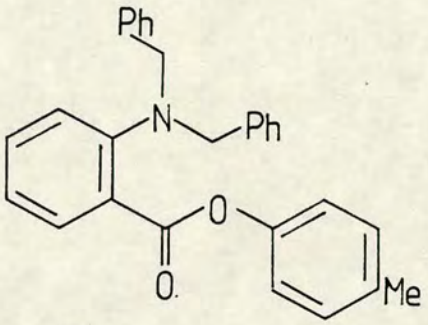
SCHEME 88

However, where the bridging *NH* of (212) was replaced by *NMe*, homolysis of the *N*-allyl bond occurs and a small quantity of *N*-methylcarbazole (6%) was obtained on pyrolysis. Therefore it was expected that pyrolysis of the *N*-acetyl, *N*-allyl derivative (213) at 650°C would yield *N*-acetyl-2-methylcarbazole (214) (Scheme 89), and thus 2-methylcarbazole, after deprotection of the *NH* function.



SCHEME 89

However, this precursor system could not be prepared, either by acetylation of the *N*-allyl group or allylation of the *N*-acetyl group, and therefore an alternative radical generator was sought. Thus, it was hoped that pyrolysis of the *N*,*N*-bibenzyl precursor (215) at 600°C[114] would give *N*-benzyl-2-methylcarbazole, and hence 2-methylcarbazole, after removal of the *N*-benzyl group, by catalytic hydrogenolysis. However this route could not be

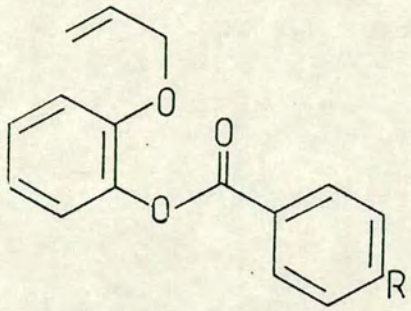


(215)

applied, because only the monobenzyl compound could be prepared.

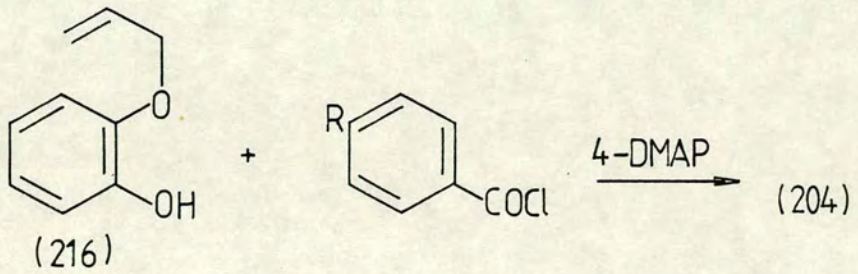
Therefore a new approach was taken which involved modification of the bridging linkage, in such a way that on pyrolysis the Boekelheide rearrangement[113] could not take place, but which still enabled the expulsion of a leaving group (eg CO_2) and hence generation of the phenyl radical (ie Scheme 68). Thus two modified linkages were introduced, ie (204) where the ester group is transposed and (205), which contains an azo linkage. The preparation and pyrolysis of these systems is discussed below.

2 Preparation and Pyrolysis of the (2-Allyloxy)-phenyl Benzoate System



(204; R=H,Me)

The ester system (204) was prepared in 70% yield by the 4-DMAP-catalysed reaction of (2-allyloxy)phenol (216) (obtained by mono *O*-alkylation of catechol) and the appropriate benzoyl chloride (Scheme 90).



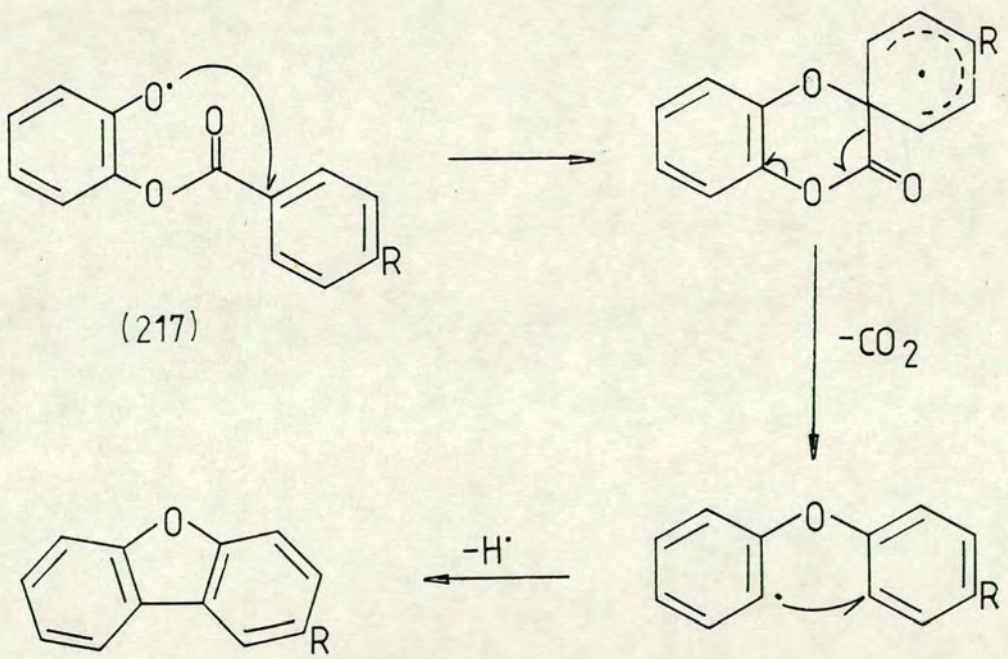
(216)

SCHEME 90

The mass spectra of these compounds differ from their expected thermal breakdown, and in fact show a similar fragmentation pattern to the related aryl ester system, discussed in Section D. Thus α-cleavage of the ester linkage, producing a peak at M-149, is followed by loss of carbon monoxide.

However under F.V.P. conditions, these compounds did not behave like the related ester systems. Thus pyrolysis of (2-allyloxy)phenyl benzoate, (204, R=H) at 650°C, produced some polymeric material and a brown oil, which was shown by g.c./m.s. to contain only a small amount of the expected dibenzofuran, *m/z* 168. The other detected components were identified as allylbenzene *m/z* 118, naphthalene *m/z* 128, together with a trace of biphenyl *m/z* 154, by correlation with authentic samples. Similarly pyrolysis of (2-allyloxy)phenyl 4-methylbenzoate (204, R=Me) at 650°C, gave largely polymeric material together with a trace of 2-methyldibenzofuran *m/z* 182, and a trace of 2-methylnaphthalene, *m/z* 142.

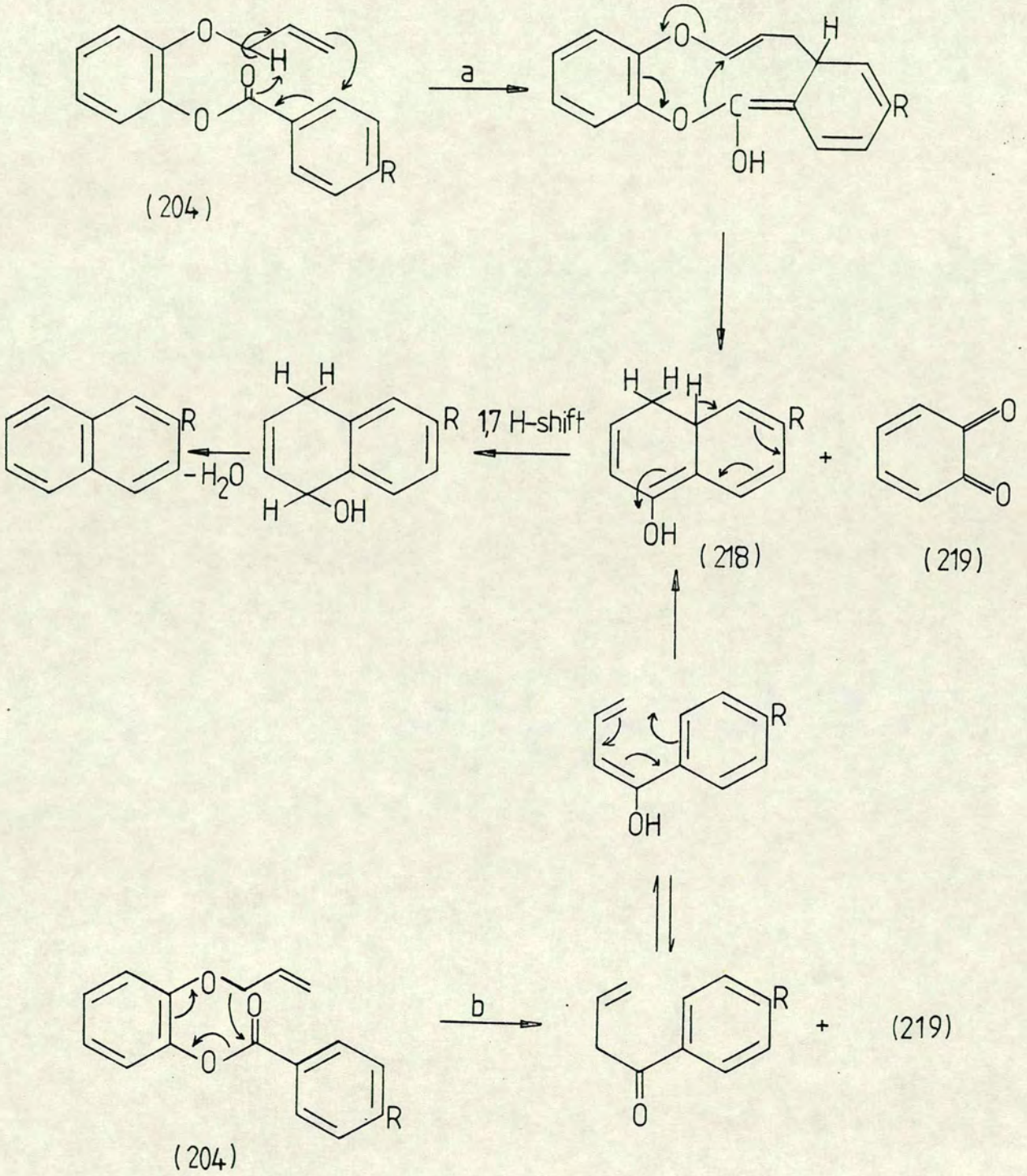
The dibenzofuran system is almost certainly formed from the phenoxyl radical (217), by the expected route shown in Scheme 91, which is analogous to that proposed for the related phenoxyl species (Section D.2, Scheme 68).



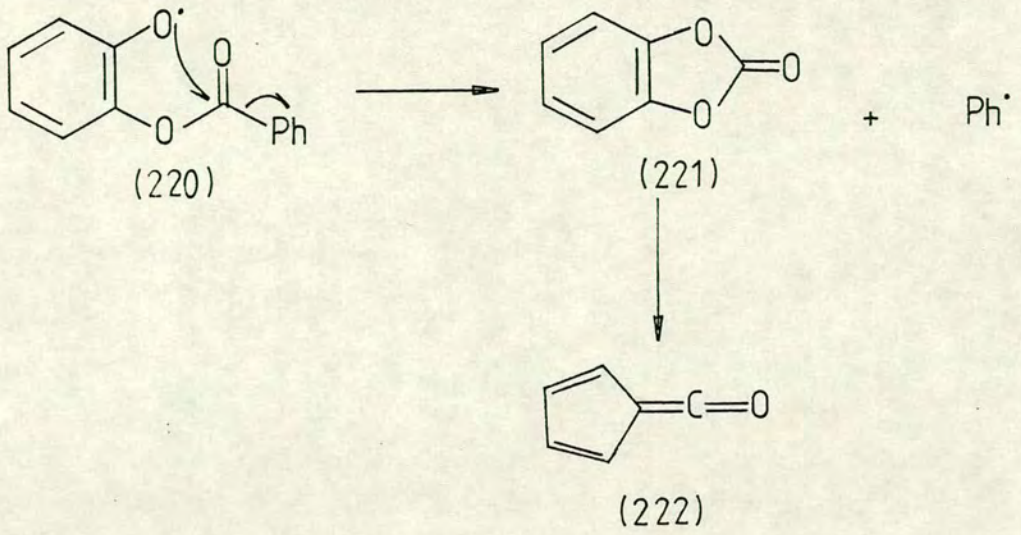
SCHEME 91

However, the low product yield indicates that unlike the previous ester system, many other reactions are occurring under F.V.P. conditions. The formation of 2-methylnaphthalene from the 4-methylbenzoate derivative (204, R=Me) suggests that the naphthalene system is derived from the methyl-substituted benzene ring, by a concerted mechanism. Thus two possible routes have been proposed (Scheme 92), each involving formation of the dihydronaphthol intermediate (218), and hence the naphthalene system, *via* a 1,7 hydrogen shift and loss of water. Furthermore, some polymeric material may be derived from *o*-quinone (219), which is also produced by these routes (Scheme 92).

On the other hand, the presence of allylbenzene and biphenyl indicate the formation of phenyl radicals. However these species do not couple efficiently[115], even under F.V.P. conditions which favour intermolecular reactions[116], as they preferentially undergo hydrogen abstraction to give benzene, which would not be detected by standard work-up and g.c. conditions. Therefore, formation of detectable quantities of these coupling products suggests that aryl radicals are being produced to a considerable extent. These species can result by the mechanism proposed in Scheme 93.



SCHEME 92

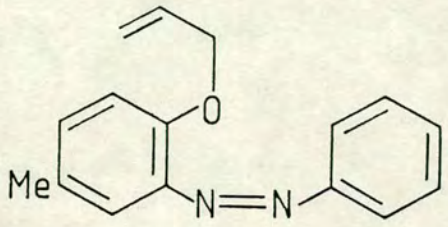


SCHEME 93

Thus, the phenoxyl radical (220), once generated, could form a 5-membered ring species by attack at the carbonyl group (in preference to 7-membered spiro-formation, eg Scheme 91), and thereafter eject an aryl radical to give *o*-phenylene carbonate (221). In fact (221) is thermally labile and is known[117] to decarboxylate under F.V.P. conditions to form the ketene (222), which could then polymerise, and hence account for the major product formed in this system.

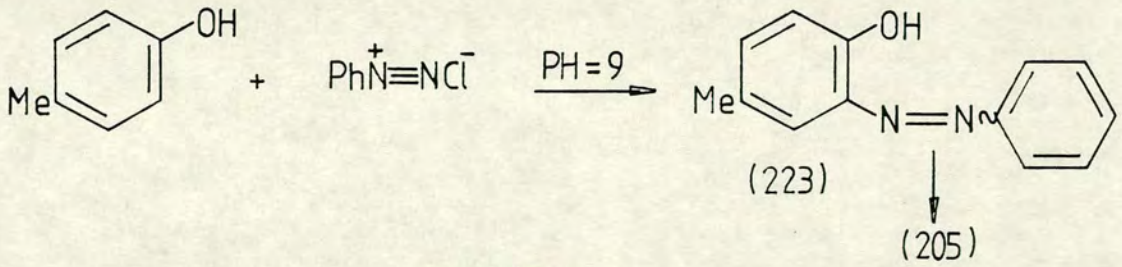
These reactions are of mechanistic interest, however this system obviously cannot be applied to the synthesis of carbazole derivatives, and therefore this area was investigated no further.

3 Preparation and Pyrolysis of (2-Allyloxy-5-methyl)-azobenzene



(205)

The azo linkage can be easily prepared by the electrophilic substitution of a phenolate anion with a diazonium salt. Where the *para*-position of the phenoxide ion is already substituted, then *ortho*-coupling occurs; thus *p*-cresol was coupled with phenyldiazonium chloride to form the hydroxycompound (223). Subsequent *O*-alkylation of (223) with allyl bromide under basic conditions then yielded the radical precursor (205, Scheme 94).



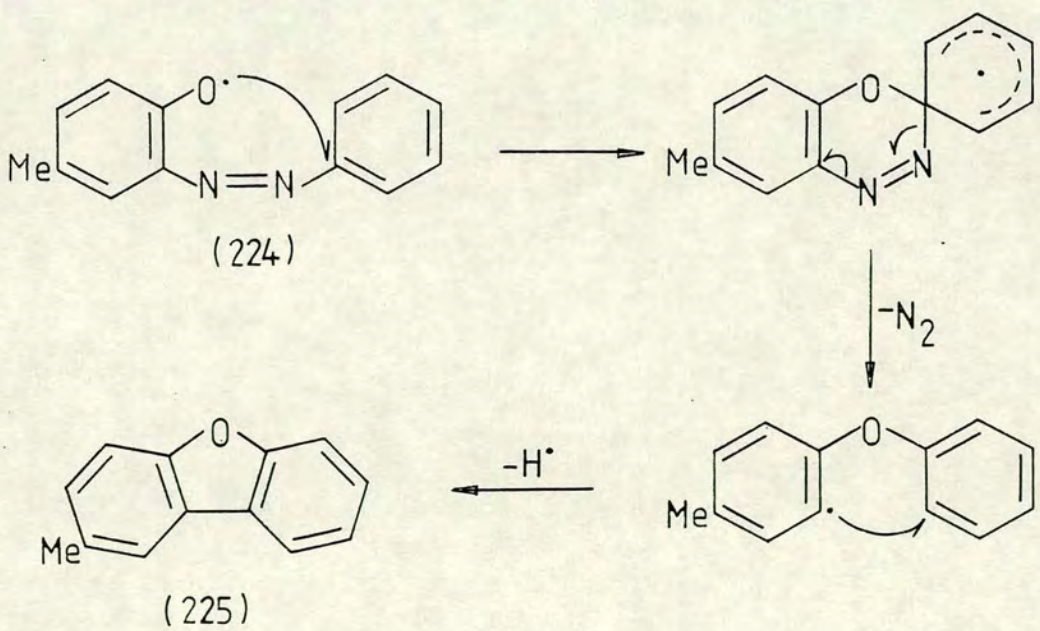
SCHEME 94

The mass spectrum of this compound shows a major peak at *m/z* 77, which indicates that fragmentation proceeds by loss of the unsubstituted phenyl group.

Flash vacuum pyrolysis of (205) at 650°C (10^{-3} Torr)

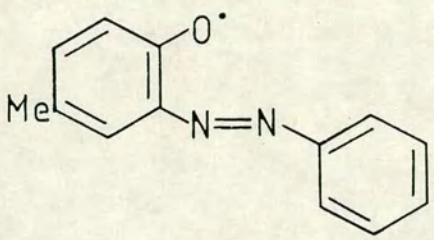
produced a yellow oil and some polymeric material, although approximately 15% of the precursor decomposed in the inlet tube (see Experimental, Section G). The oil was separated from the polymer by distillation, and a yellow solid (28%) was isolated by column chromatography on silica. This was identified by g.c. and g.c./m.s. comparison with an authentic sample as 2-methyldibenzofuran (225). G.c. analysis of the other fractions indicated the presence of numerous minor volatile components, but none of these were identified.

Thus formation of the expected product (225) indicates that the phenoxyl radical (224), once generated, follows the same course as the related (2-aryloxycarbonyl)phenoxyl radicals (Section D), via loss of N_2, instead of CO_2 (Scheme 95). However unlike the previous system, the yield of (225)



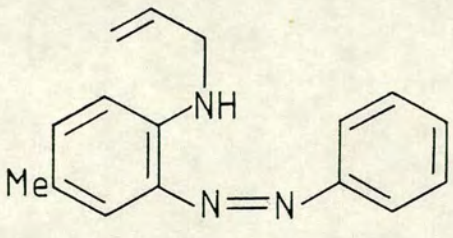
SCHEME 95

is much reduced, and thus many other reactions may occur under pyrolysis. Furthermore, significant *E*-*Z* isomerisation of the radical species (224) can occur during pyrolysis[118], and where the radical exists in the *E*-configuration (226), formation of the spirodienyl intermediate may be disfavoured, and hence (225) may follow



(226)

an alternative reaction pathway involving fragmentation and/or polymerisation. Therefore, due to these competing reactions and the envisaged inaccessibility of the precursor system (226^{a}), this process cannot be developed as a route

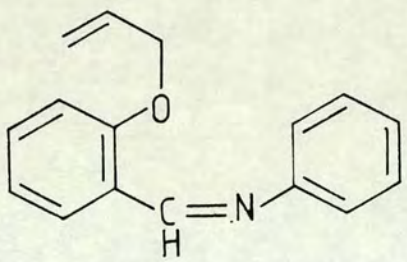


(226^{a})

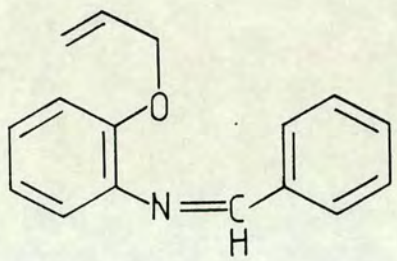
to the carbazole system.

F Preparation and Pyrolysis of (2-Allyloxybenzylidine)-aniline and Benzylidine-(2-allyloxyaniline)

In the previous section, phenoxyl radical systems which contain a 'built-in' leaving group (eg CO_2, N_2) have been studied. Therefore it was hoped to extend the synthetic scope of the radical system by the generation of other similar systems. Thus the imino-bridged compounds (227) and (228), which could potentially lose HCN, were an obvious choice for investigation.

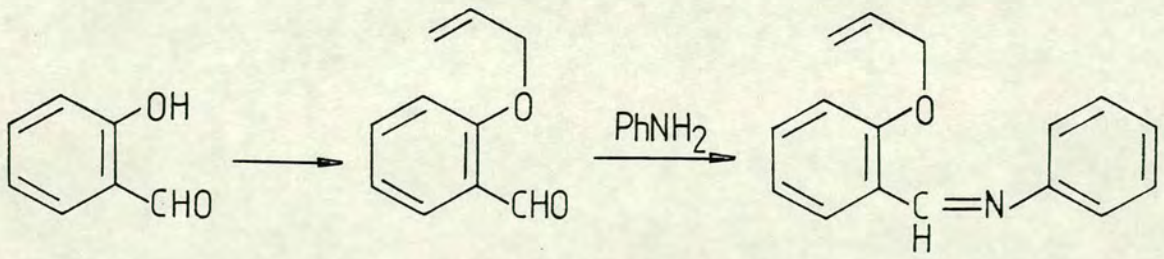


(227)



(228)

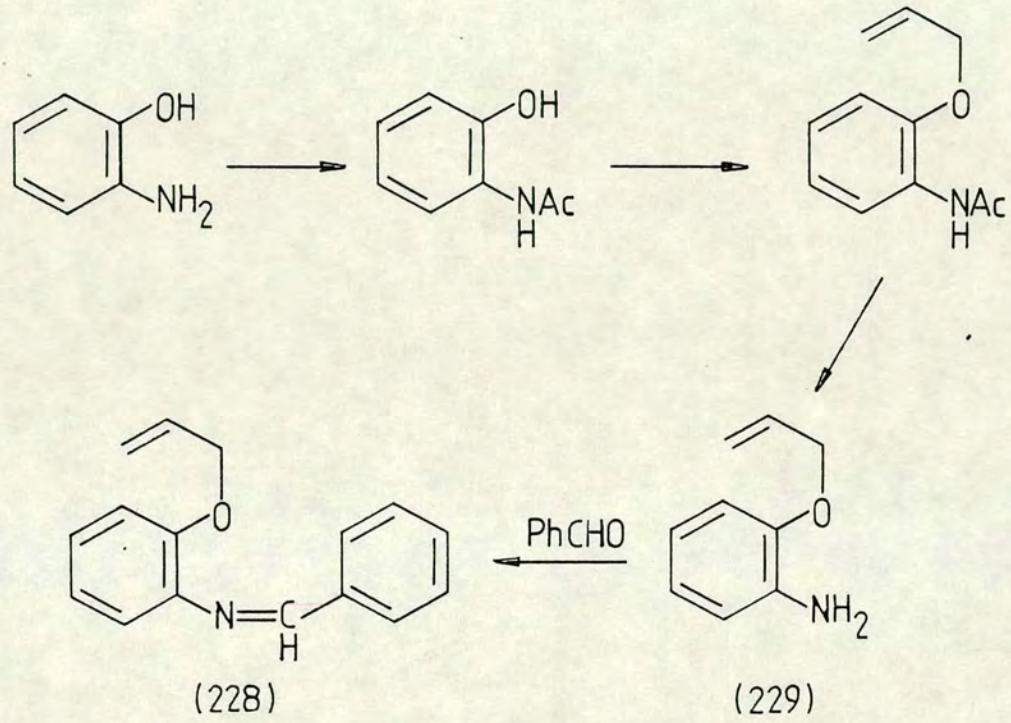
Compound (227) was prepared by the route depicted in Scheme 96, which involves the *O*-alkylation of salicylaldehyde with allyl bromide to give (229), followed by reaction of (229) with aniline. The benzylidine system



(229) (227)

SCHEME 96

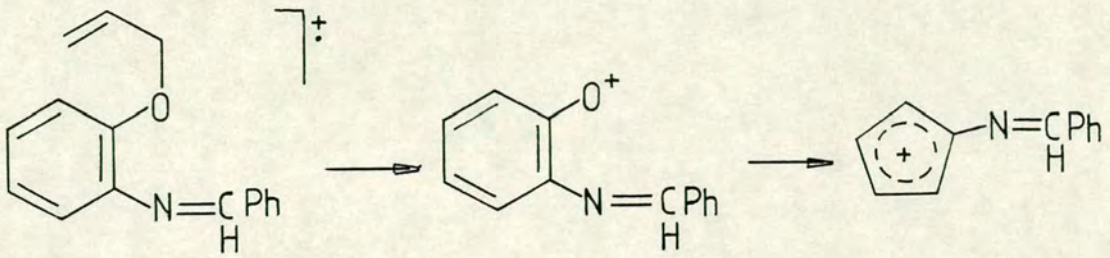
(228) was prepared by a more complex route, shown in Scheme 97. Thus 2-aminophenol was *N*-acetylated to allow *O*-alkylation of the hydroxyl function. The protecting group was then removed by acid hydrolysis to form (229), and this in turn was condensed with benzaldehyde to give (228).



(228) (229)

SCHEME 97

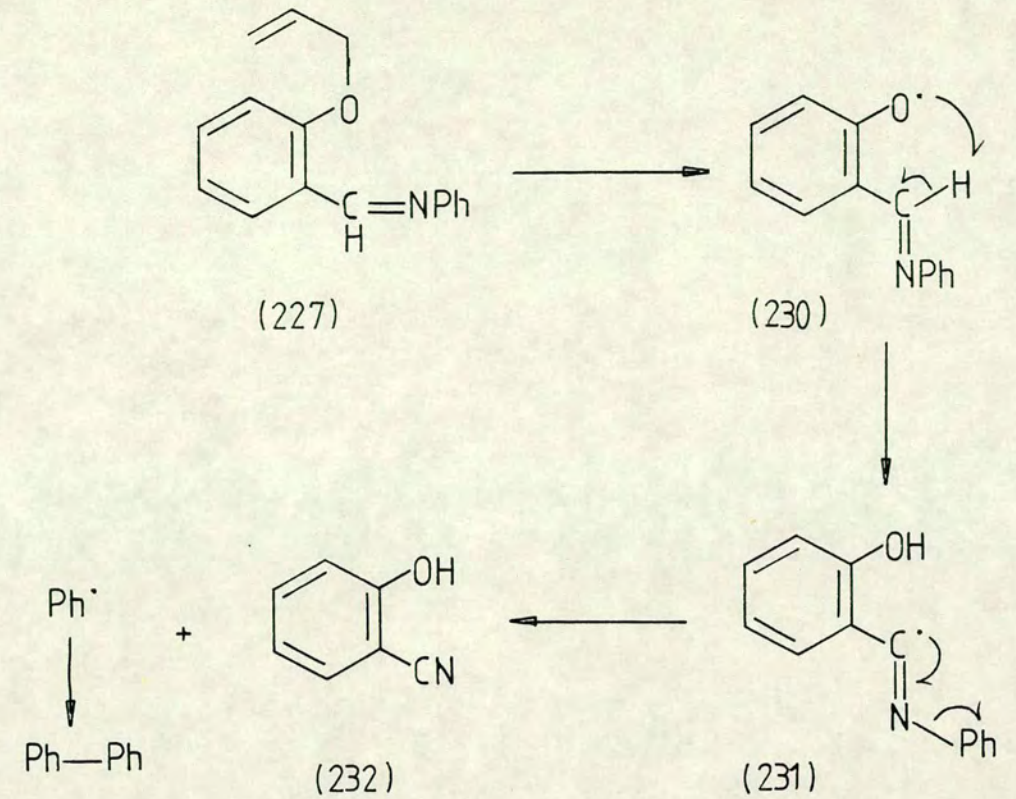
The mass spectrum of (227) differs from its expected thermal breakdown, as the major fragmentation involves cleavage of the *N*-phenyl bond to give a peak at *m/z* 77. However the mass spectrum of (228) shows a fragmentation pattern which is compatible with the first step of its expected thermal decomposition, and thus involves cleavage of the *O*-allyl bond, followed by loss of CO (Scheme 98).



m/z 237 m/z 196 m/z 168

SCHEME 98

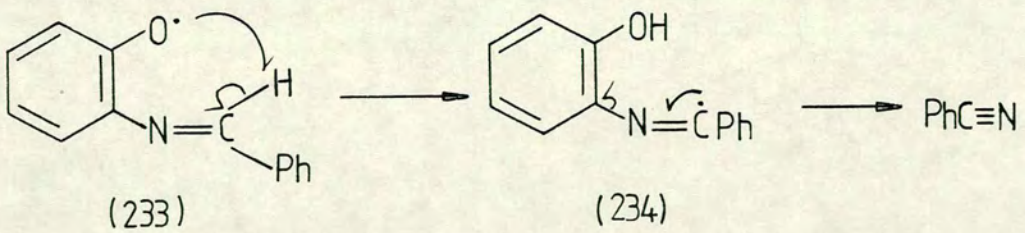
Furthermore, these compounds also behaved differently under F.V.P. conditions. Pyrolysis of (227) at 650°C (10^{-3} Torr) did not produce any cyclised products but instead gave a crystalline solid identified as *o*-cyanophenol (39%) by melting point correlation, and some droplets containing volatiles and a trace of biphenyl, which were detected by g.c. Formation of these compounds can arise, from the phenoxyl radical (230), by the route depicted in Scheme 99. Thus, the phenoxyl radical can abstract a hydrogen atom through a 5-membered transition state, to form the species (231), and hence *o*-cyanophenol (232) by ejection of the phenyl radical. However aryl radicals do not couple efficiently[115] (as stated in Section E), and therefore the presence of a detectable quantity of biphenyl is consistent with the formation of a moderate yield of (232).



SCHEME 99

On the other hand, pyrolysis of (228) under the same conditions, produced a black oil, which was shown by g.c./m.s. to contain 2-phenylbenzoxazole *m/z* 195 as the major detected product, together with traces of benzoxazole *m/z* 119 and benzonitrile *m/z* 103.

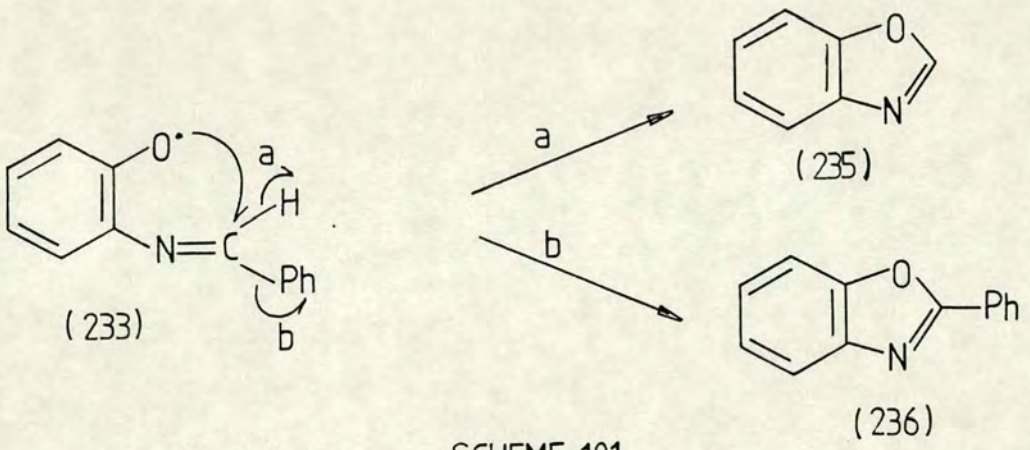
Formation of benzonitrile can result from the phenoxyl radical (233), by the mechanism shown in Scheme 100, which is analogous to that proposed for *o*-cyanophenol



SCHEME 100

formation, in Scheme 99. Thus (233) can abstract the alkyl hydrogen atom through a 6-membered transition state, to form the species (234) and hence benzonitrile, by ejection of the aryl radical. However this is only a minor pathway, unlike reaction of the (2-oxybenzylidine)-aniline system (227), and therefore it is not surprising that no biaryls have been detected.

Formation of the benzoxazoles (235) and (236) can result by the competing pathway shown in Scheme 101. Thus, the phenoxyl radical (233) can attack the unsaturated

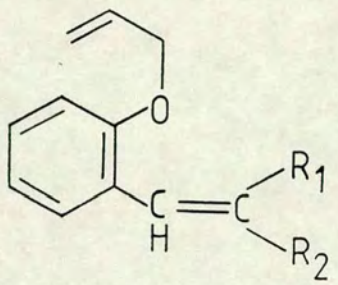


SCHEME 101

carbon centre directly, to form the 5-membered ring product via ejection of one of the substituent groups. Indeed formation of (236), as the major product, indicates that H• is lost in preference to the phenyl radical. Interestingly, this reaction pathway is analogous to that proposed for the (2-allyloxy)phenylbenzoate system (Section E.2, Scheme 93), and therefore it was hoped that other 5-membered ring-closures of this type could be investigated. Hence a range of related vinylbenzene systems were studied, and the results are discussed in the following section.

G Preparation and Pyrolysis of (2-Allyloxy)stilbene and Related Compounds

As stated in the previous section, it was hoped to investigate further examples of 5-membered ring formation achieved by phenoxyl radical substitution reactions. Thus (2-allyloxy)stilbene (237) was selected, as a likely precursor, and a range of related compounds (238-241) were prepared and pyrolysed.



(237) ; R_1 = Ph , R_2 = H

(238) ; " CO_2Me, " CO_2Me

(239) ; " CN , " CO_2Me

(240) ; " CN , " CN

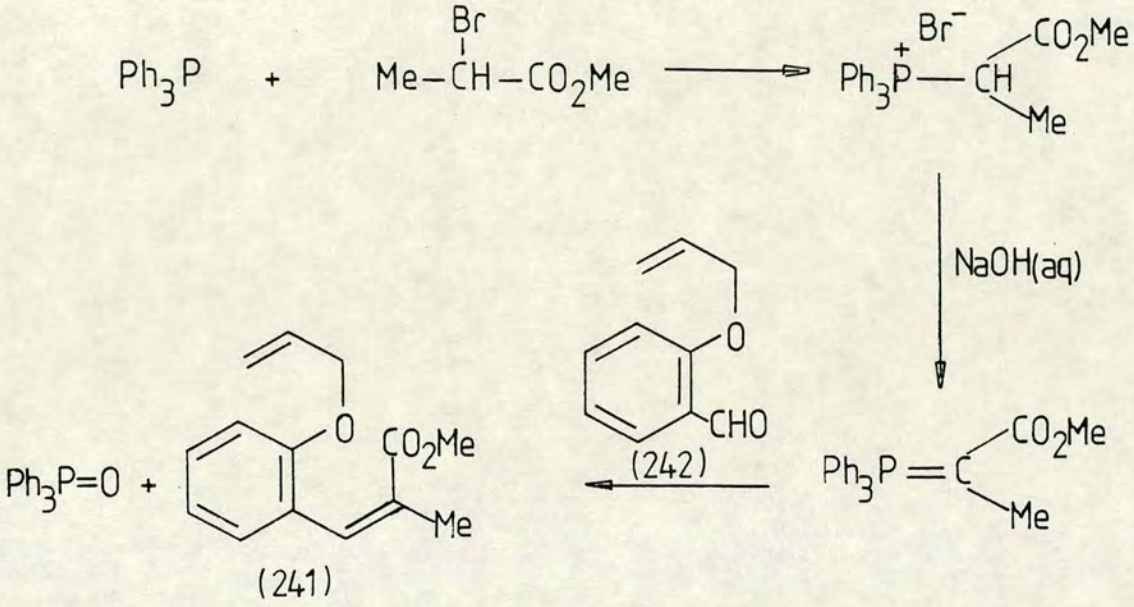
(241) ; " Me , " CO_2Me

1. Preparation of Precursor Systems

Compounds (237) and (241) were each prepared from (2-allyoxy)benzaldehyde (242) by a Wittig reaction, whereas (238), (239) and (240) were prepared from (242) by a knoevenagel reaction. The details of each procedure are

discussed below.

Thus (237) was prepared in moderate yield (37%) by reaction of benzyltriphenylphosphonium bromide, sodium ethoxide and (2-allyloxy)benzaldehyde. Similarly, (241) was prepared from methyl D.L-2-bromopropionate by the route shown in Scheme 102. However, the final step



SCHEME 102

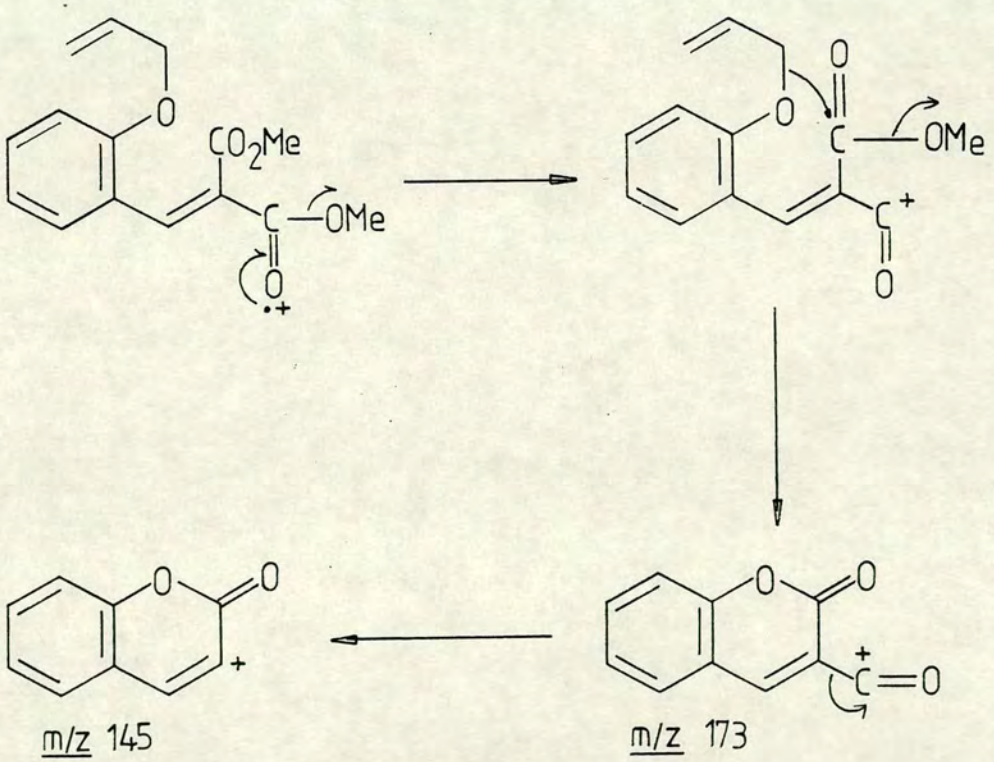
of this reaction did not go to completion, and therefore excess (242) was removed as a water soluble hydrazone, by using Girard's "T" reagent.

Compounds (239) and (240) were prepared in high yield from methyl cyanoacetate and malononitrile respectively, by reaction with (242) in the presence of piperidine and acetic acid[119]. However preparation of (238) from (242) was carried out under nitrogen, and required the presence of pyridine as base and two equivalents of $TiCl_4$, which may promote the reaction by acting as a dehydrating agent.

2. Mass Spectra and Pyrolysis of (2-Allyloxy)stilbene and Related Compounds

The mass spectrum of (237) shows a fragmentation pattern which is consistent with the first step of its expected thermal breakdown, and analogous to that observed for the related benzylidine-(2-allyloxyaniline) system [Section F , (237), Scheme 98). Hence this involves cleavage of the *O*-allyl bond, producing a peak at *m/z* 195 followed by loss of CO to give a base peak at *m/z* 167.

However, the other compounds undergo a different fragmentation pattern. Thus (238) can breakdown by the pathway shown in Scheme 103, whereby loss of a methoxy group is followed by loss of the allyl and a second methoxy group to give a base peak at *m/z* 173. Hence the peak at *m/z* 145

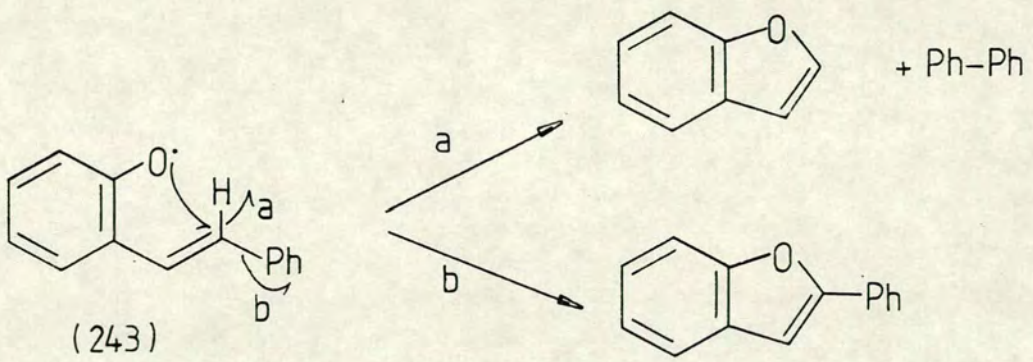


SCHEME 103

can result by further loss of CO. Compounds (239), (240) and (241) undergo a related fragmentation pattern involving loss of a methoxy group, followed by decarbonylation and then loss of the allyl group, to show peaks at M-31, M-59 and M-100 respectively. However, unlike the related benzylidine (228) and stilbene (237) systems, the mass spectra of these compounds are further complicated by the existence of several other competing fragmentation pathways.

Pyrolysis of (237) at 650°C (10^{-3} Torr) produced 2-phenylbenzofuran (55%), identified by melting point correlation, and traces of benzofuran and biphenyl, which were detected by g.c.

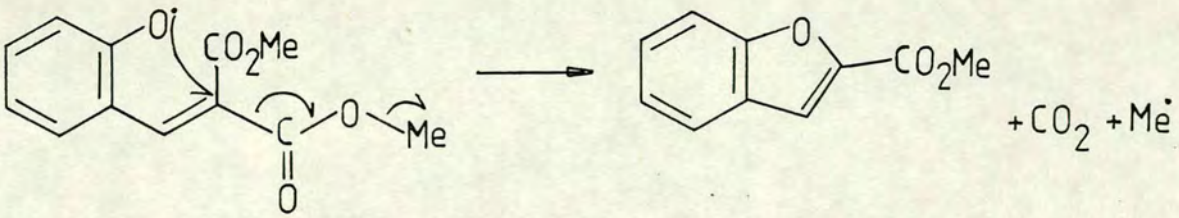
Formation of these products can result by a mechanism analogous to that proposed for the formation of the benzoxazole system from benzylidine-(2-allyloxyaniline) (228) (Section F, Scheme 101); the relevant mechanism is shown in Scheme 104.



SCHEME 104

Thus the phenoxyl radical (243) can achieve 5-membered ring-closure by attack at the unsaturated carbon centre, with subsequent ejection of one of the substituent groups. Furthermore, as observed in the related benzylidine system (Section F), the hydrogen atom is lost in preference to the phenyl group, and hence 2-phenylbenzofuran can be obtained in moderately high yield (55%).

The related vinylbenzene systems (238)-(241) were also pyrolysed under the same conditions. Hence, dimethyl (2-allyloxyphenyl)methylenemalonate (238) gave a crystalline solid, identified as methyl benzofuran-2-carboxylate (95%) by melting point correlation. No other products were detected. Thus formation of this compound is achieved by a route analogous to that described above, except that in this case, 5-membered ring-closure results in loss of the carbomethoxy group, as CO_2 and a methyl radical (Scheme 105).



SCHEME 105

Similarly pyrolysis of (239) gave 2-cyanobenzofuran (52%), identified by g.c./m.s. *m/z* 143. However, during work-up column chromatography was required to remove some polymeric material, which may result from the decomposition

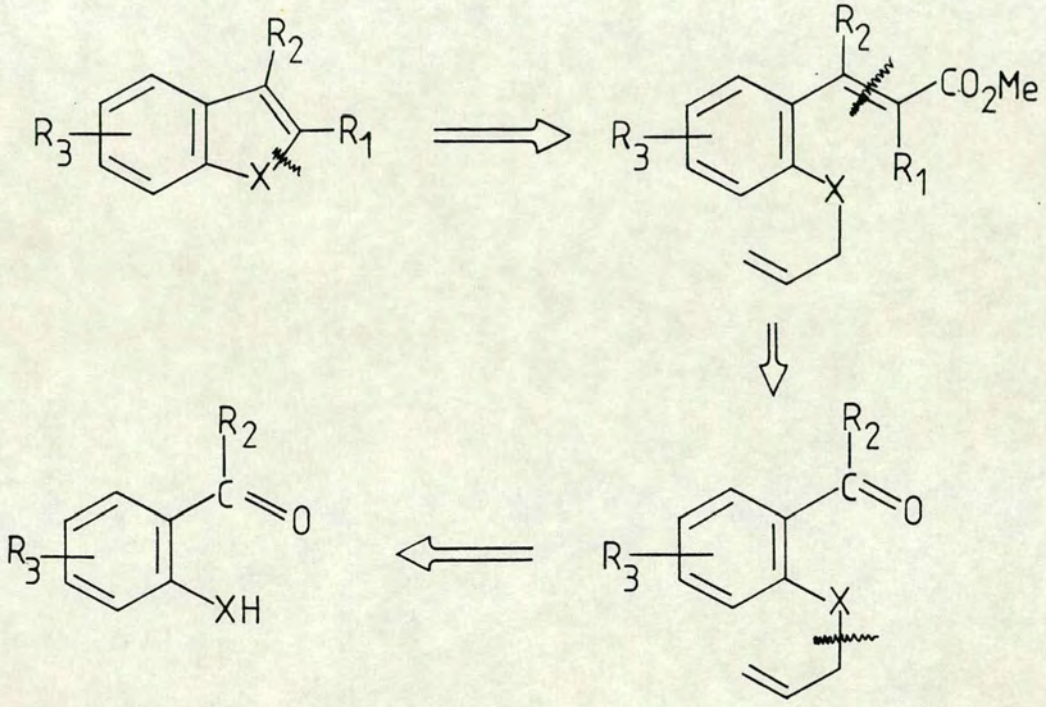
products that are formed in the inlet, due to the low volatility of (239).

Conversely, pyrolysis of (2-allyloxyphenyl)methylene-malononitrile (240) did not give the expected cyclised product, but instead produced some polymeric material and 30% by weight of an unidentified crystalline solid, whose mass spectrum shows a base peak at *m/z* 168, and a major breakdown peak at *m/z* 143.

Therefore it can be deduced that the driving force for the 5-membered ring formation results from the ejection of a suitable radical leaving group (eg Ph$^{\cdot}$, H$^{\cdot}$, "CO_2Me"). However, pyrolysis of the (2-allyloxy)stilbene system (237) shows that, where the site of radical attack is substituted with two suitable leaving groups, then there is a slight loss of selectivity (ie Scheme 104).

Therefore it was interesting to pyrolyse methyl (2-allyloxyphenyl)methylenepropionate (241), where loss of a methyl radical, a common radical leaving group[120], could compete with ejection of the carbomethoxy group. In the event analysis of the pyrolysate by g.c. and g.c./m.s. showed the presence of some minor volatile components, together with 2-methylbenzofuran *m/z* 132 as the major product. However, no methyl benzofuran-2-carboxylate was detected, and thus specific loss of the carbomethoxy group has been observed.

The specific ejection of the carbomethoxy group, observed in this system, has great synthetic potential. Hence, this route could be applied to the synthesis of a wide range of benzofurans, and by extension, to the preparation of benzothiophenes, and indoles (Scheme 106).



SCHEME 106

EXPERIMENTAL

A Abbreviations

n.m.r.	nuclear magnetic resonance
δ	chemical shift
s	singlet
d	doublet
t	triplet
q	quartet (in ^{1}H n.m.r. spectra)
q	quaternary (in ^{13}C n.m.r. spectra)
m	multiplet
br	broad
J	coupling constant
m.s.	mass spectrometry
M^{+}	mass of molecular ion
m/z	mass to charge ratio
t.l.c.	thin layer chromatography
g.c.	gas-liquid chromatography
g.c./m.s.	gas-liquid chromatography/mass spectrometry
m.p.	melting point
b.p.	boiling point
h	hours
min	minutes
mol	moles
mmol	millimoles
D.M.F.	*N*,*N*-Dimethylformamide
T.H.F.	Tetrahydrofuran
4.D.M.A.P.	4-Dimethylaminopyridine

B Instrumentation and General Techniques

Nuclear Magnetic Resonance Spectroscopy

(i) ^{1}H N.m.r. spectra were recorded by Mr. J.R.A. Millar, Miss H. Grant, and Dr. H. McNab on either a Bruker WP200 or a Bruker WP80 spectrometer.

(ii) ^{13}C N.m.r. spectra were recorded by Mr. J.R.A. Millar and Dr. H. McNab on a Bruker WP200 spectrometer.

All n.m.r. spectra were recorded in deuteriochloroform solutions unless otherwise stated. Chemical shifts (δ_C, δ_H) were measured in parts per million relative to tetramethylsilane (δ=0.0).

Mass Spectrometry

Mass spectra were recorded by Miss E. Stevenson on an A.E.I. MS902 spectrometer and by Mr. A. Thomson on a Kratos MS50TC instrument.

Chromatography

(i) Qualitative gas-liquid chromatography was carried out on a Carlo Erba Strumentazione Fractovap 2450 instrument, fitted with a flame ionisation detector, and nitrogen was used as a carrier gas. Most samples were run on a 1.5m x 4.5mm column of 5% SE30 on Gas chrom (80-100 mesh), although some samples were run on 5% Carbowax on Gas chrom (80-100 mesh).

(ii) Thin-layer chromatography was carried out using pre-coated plastic sheets (0.25mm silica gel or 0.2mm aluminium oxide) impregnated with UV fluorescent indicator from Macherey-Nagel.

(iii) Dry flash chromatography was carried out on silica gel (Merck, grade 60, 230-400 mesh, 60Å), by the method of Harwood[121]. Ether and n-hexane was generally used as the solvent system, with 10% increments in the more polar component per fraction.

Gas-liquid Chromatography/Mass Spectrometry

G.c./m.s. results were obtained from a Pye series 104 chromatograph coupled to a V.G. Micromass 12 spectrometer operated by Miss E. Stevenson.

Elemental Analysis

Microanalyses were obtained using a Carlo Erba Elemental Analyser, Model 1106, operated by Mrs. E. McDougal.

C Pyrolysis Apparatus and General Techniques

Flash vacuum pyrolysis was carried out on apparatus based on the design of W.D.Crow, Australian National University. The important features of this apparatus are shown in Figure 1. The sample was volatilised from a horizontal inlet tube, heated by a Buchi Kugelrohr oven, into a silica furnace tube (30 x 2.5 cm). This was maintained at temperatures in the range 600-1000°C by a Stanton Redcroft Laboratory tube furnace LM8100, the temperature being measured by a platinum/platinum 13% rhodium thermocouple situated at the centre of the furnace. The products were collected in a U-shaped trap cooled in liquid nitrogen and situated at the exit point of the furnace. The apparatus was evaluated to 10^{-2} - 10^{-3} Torr by an Edwards Model ED100 high capacity rotary oil pump,

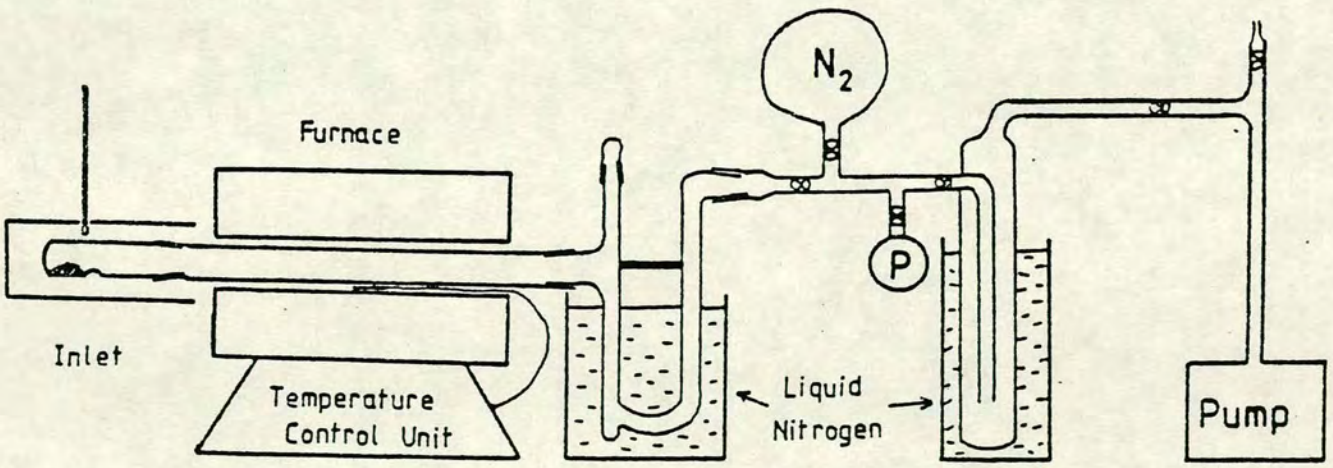


FIGURE 1

Small scale pyrolyses were generally carried out with sample sizes of 0.1-1.0 mmol. The entire pyrolysate was dissolved in deuteriochloroform and analysed by ^1H n.m.r., g.c. and in some cases g.c./m.s. Products were generally characterised by comparison with authentic samples. In most cases two independent methods of identification were used; comparison with an authentic sample by g.c. and comparison with the ^1H n.m.r. spectrum of an authentic sample. In some cases comparison of m.s. breakdown patterns was also used. Absolute yields were obtained from the ^1H n.m.r. spectra by addition of cyclohexane (5 µl) as an integral calibrant (yields calculated by this method are estimated to be correct to ±5%).

For preparative scale experiments sample sizes of 0.1-2 g were used.

In the sections which deal with pyrolysis experiments the conditions are quoted as follows: substrate, quantity pyrolysed, inlet temperature, furnace temperature, pressure range, pyrolysis time and products.

D The Generation and Cyclisation of 2-(*N*-Substituted carbamyl)phenoxyl Radicals

1. Preparation of 2-Hydroxybenzamides

Phenyl salicylate (10 g, 0.047 mol) and the appropriate amine (0.059 mol) were heated together for 3h at 180-200°C, in a flask fitted with a short air condenser. The hot melt was poured into ethanol (25 ml), charcoal was added to adsorb impurities, and was removed by filtration. The product then crystallised on cooling.

The following compounds were prepared by this method:

N-Phenyl-(2-hydroxy)benzamide (70%), m.p. 129-131°C (from ethanol) (lit[123] 131-132°C); δ_H 9.79 (1H, bs, *OH*), 8.03-6.89 (9H, m) and 3.82 (1H, bs, *NH*); *m/z* 213 (M^+, 20%), 121(33), and 93(100).

N-Methyl-*N*-phenyl-(2-hydroxy)benzamide (69%), m.p. 107-109°C (from ethanol) (lit[124] 111-112°C); δ_H 10.87 (1H, bs, *OH*), 7.57-6.20 (9H, m), and 3.57 (3H, s, N*CH*$_3$); *m/z* 227 (M^+, 15%), 121(44), 107(100), 93(10), and 77(12).

N,*N*-Diphenyl-(2-hydroxy)benzamide (21%), m.p. 193-194°C (from ethanol) (lit[125] 193°C); δ_H 10.70 (1H, bs, *OH*), 7.44-6.44 (14H, m); δ_C 172.30 (q), 161.24 (q), 143.83 (q), 133.22, 130.51, 129.26, 127.15, 126.71, 117.92, 117.81, and 116.09 (q); *m/z* 289 (M^+, 100%), 169(100), 121(88), 93(28), and 77(26).

N-*Ethyl*-N-*phenyl*-*(2-hydroxy)benzamide* (15%), m.p. 74-76°C (from ethanol); δ_H 10.98 (1H, bs, *OH*), 7.33-6.33 (9H, m), 4.03 (2H, q, *CH*$_2$), and 1.21 (3H, t, *CH*$_3$); δ_C (D.E.P.T.)

132.39, 130.11, 129.42, 127.32, 127.06, 117.57, 117.47, 46.31, and 12.35.

2. Preparation of *N*-Substituted-(2-allyloxy)benzamides

The appropriate amide (0.02 mol) was added to DMF (50 ml), containing anhydrous potassium carbonate (2.76 g, 0.02 mol). Allyl bromide (2.42 g, 0.02 mol) was added dropwise and the mixture was stirred at room temperature for 21h.

Water (100 ml) was then added and the solution was extracted with ether (3x50 ml). The combined organic extracts were washed with water (3x50 ml), dried ($MgSO_4$) and the solvent was removed *in vacuo*. The following compounds were prepared by this method:

N-*Phenyl-(2-allyloxy)benzamide* (82%), m.p. 51-53°C (from n-hexane/ethyl acetate) (Found: C, 76.2; H, 5.65; N, 5.5. $C_{16}H_{15}NO_2$ requires C, 75.9; H, 5.9; N, 5.55%); δ_H 9.97 (1H, bs, *NH*), 8.89 (1H, m), 7.69-7.63 (2H, m), 7.48-7.29 (3H, m), 7.14-6.96 (3H, m), 6.18 (1H, m), 5.57-5.41 (2H, m), and 4.69 (2H, m); δ_C 162.92 (q), 156.11 (q), 138.24 (q), 132.85, 132.15, 131.55, 128.69, 123.74, 121.90 (q), 121.53, 119.88, 119.69, 112.72, and 69.98; *m/z* 253 (M^+, 40%), 161(100), and 133(27).

N-*Methyl*-N-*phenyl-(2-allyloxy)benzamide* (98%), m.p. 68-70°C (from n-hexane/ethyl acetate) (Found: C, 76.8; H, 6.35; N, 5.2. $C_{17}H_{17}NO_2$ requires C, 76.4; H, 6.4; N, 5.25%); δ_H 7.31-6.80 (9H, m), 5.93 (1H, m), 5.43-5.18 (2H, m), 4.35

(2H, m), and 3.46 (3H, s, NCH_3); δ_C 168.86 (q), 153.95 (q), 143.67 (q), 132.98, 129.85, 128.46, 128.20, 127.03 (q), 126.48, 126.24, 120.27, 116.90, 111.85, 68.66, and 36.91; *m/z* 267 (M^+, <1%), 227(17), 161(8), and 107(100).

N,N-*Diphenyl-(2-allyloxy)benzamide* (80%), m.p. 95-97°C (from ethanol) (Found: C, 80.1; H, 5.75; N, 4.15. $C_{22}H_{19}NO_2$ requires C, 80.25; H, 5.8; N, 4.25%); δ_H 7.60-6.59 (14H, m), 5.98 (1H, m), 5.44-5.24 (2H, m), and 4.30 (2H, m); δ_C 168.87 (q), 154.07 (q), 142.93 (q), 132.93, 130.34, 129.08, 128.37, 127.37, 127.16 (q), 126.09, 120.34, 117.13, 111.78, and 68.70; *m/z* 329 (M^+, 20%), 167(20), 162(100), 133(10), and 121(10).

N-*Ethyl*-N-*phenyl-(2-allyloxy)benzamide* (68%), m.p. 39-41°C (from ethanol) (Found: C, 77.3; H, 6.95; N, 4.9. $C_{18}H_{19}NO_2$ requires C, 76.9; H, 6.75; N, 4.9%); δ_H 7.39-6.98 (7H, m), 6.75 (1H, m), 6.56 (1H, m), 5.98 (1H, m), 5.33-5.22 (2H, m), 4.35 (2H, m), 3.95 (2H, q, CH_2), and 1.21 (3H, t, CH_3); δ_C 188.62 (q), 179.50 (q), 177.54 (q), 175.41, 175.20, 168.37, 153.90, 142.08, 133.04 (q), 132.47, 131.46, 121.64, 116.87, 68.69, 43.89, and 12.98; *m/z* 281 (M^+, 26%), 161(100), 33(15), and 41(30).

3. Pyrolysis of *N*-Substituted-(2-allyloxy)benzamides

N-Phenyl-(2-allyloxy)benzamide

0.59 g (0.23 mmol), 120°C, 650°C, 5×10^{-3} Torr, 60 min. ^1H n.m.r. spectroscopy indicated that starting material was recovered (37%); δ_H 7.40-6.80 (9H, m), 6.05

(1H, m), 5.25-5.10 (2H, m), and 3.40 (2H, m).

Pyrolysis was repeated at furnace temperatures of 750°C and 850°C. In each case, ^{1}H n.m.r. spectroscopy revealed the absence of starting material, and showed a series of broad peaks, indicative of polymer formation. Furthermore, the g.c. of each pyrolysate indicated the absence of volatile products.

N-Methyl-*N*-phenyl-(2-allyloxy)benzamide

1.234 g (4.6 mmol) 100°C, 650°C, 1×10^{-3} Torr, 40 min: An involatile solid and red droplets were produced. The solid was scraped from the trap and identified as 2,3-dihydro-7-hydroxy-2-phenylisoindol-1-one (0.34 g, 33%), m.p. 204-207°C (from ethyl acetate) (lit[93] 216°C) (Found: C, 74.9; H, 4.9; N, 6.25. $C_{14}H_{11}NO_2$ requires C, 74.6; H, 4.8; N, 6.2%); δ_H 8.77 (1H, s, *OH*), 7.83-7.73 (2H, m), 7.50-7.35 (3H, m), 7.18 (1H, m), 7.00-6.85 (2H, m), and 4.80 (2H, s, CH_2); δ_C 169.29 (q), 156.29 (q), 140.13 (q), 138.71 (q), 134.26, 129.04, 124.52, 119.07, 117.37 (q), 114.55, 113.63, and 51.11 (CH_2, D.E.P.T.); *m/z* 225 (M^+, 100%), 208(8), 196(14), and 77(41).

The red liquid (0.18 g) was analysed by ^{1}H n.m.r. spectroscopy and g.c. but no significant products were detected.

N,*N*-Diphenyl-(2-allyloxy)benzamide

0.052 g (0.15 mmol), 150°C, 650°C, 1×10^{-3} Torr, 30 min: A black oil and a yellow gummy material were deposited

in the cold trap. ^{1}H n.m.r. spectroscopy indicates that in each fraction, starting material is absent and g.c./m.s. shows that diphenylamine *m/z* 169 is formed.

N-Ethyl-*N*-phenyl-(2-allyloxy)benzamide

0.133 g (0.47 mmol), 100°C, 650°C, $1x10^{-3}$ Torr, 60 min: A thick yellow gum and a yellow solid were obtained. The solid was scraped from the trap and shown to be *7-hydroxy-3-methyl-2-phenylisoindol-1-one* (0.033 g, 29%), m.p. 143-145°C (from ethanol), δ_H 8.76 (1H, bs, *OH*), 7.60-7.40 (5H, m), 7.23 (1H, m), 6.97-6.87 (2H, m), 5.20 (1H, q, *CH*), and 1.56 (3H, d, CH_3), *m/z* 239 (M^+, 17%), 224(38), and 77(100). Analysis of the gum-like fraction by g.c. suggested that polymeric-type products had been formed.

E Generation and Cyclisation of (2-Alkyloxycarbonyl)-phenoxyl and (2-Alkyloxycarbonyl)thiophenoxyl Radicals

1. Preparation of Alkyl (2-allyloxy)benzoates

The appropriate alkyl salicylate (0.02 mol) was reacted with allyl bromide (4.84 g, 0.04 mol) and anhydrous potassium carbonate (5.53 g, 0.04 mol) as described in Section D2. The following compounds were prepared by this method:

Methyl (2-allyloxy)benzoate (89%) b.p. 140-144°C (1.5 Torr); (Found: C, 68.7; H, 6.3. $C_{11}H_{12}O_3$ requires C, 68.8; H, 6.25%); δ_H 7.77 (1H, m), 7.40 (1H, m), 6.98-6.90 (2H, m), 5.99 (1H, m), 5.54-5.23 (2H, m), 4.59 (2H, m), and 3.86 (3H, s); δ_C 166.52 (q), 157.94 (q), 132.95, 132.69, 131.39, 120.84 (q), 120.26, 117.01, 113.75, 69.46, and 51.56; *m/z* 192 (M^+, 28%), 161(44), 120(85), 92(43), and 41(100).

Ethyl (2-allyloxy)benzoate (84%), b.p. 129-133°C (1.5 Torr), (Found: M^+ 206.0946; $C_{12}H_{14}O_3$ requires M^+ 206.0943); δ_H 7.77 (1H, m), 7.35 (1H, m), 6.99-6.90 (2H, m), 6.08 (1H, m), 5.54-5.23 (2H, m), 4.59 (2H, m), 4.35 (2H, q, CH_2), and 1.36 (3H, t, CH_3); δ_C 166.21 (q), 157.84 (q), 132.99, 132.62, 131.40, 120.85 (q), 120.22, 117.20, 113.43, 69.29, 60.63, and 14.15 ; *m/z* 206 (M^+, 38%), 161(59), 133(22), 121(100), 120(96), 92(49), and 41(81).

2. Preparation of Methyl 2-Allyloxy-(3-methyl)-benzoate

(i) Allyl (2-allyloxy-3-methyl)benzoate

The general method of D2 was applied, using 3-methylsalicylic acid, and two equivalents each of allyl bromide and anhydrous potassium carbonate. The *benzoate* was obtained as a yellow oil (91%), b.p. 140-145°C (1.2 Torr), (Found: M^+ 232.1099; $C_{14}H_{16}O_3$ requires M^+ 232.1099); δ_H 7.63 (1H, m), 7.31 (1H, m), 7.03 (1H, m), 6.05 (2H, m), 5.44-5.19 (4H, m), 4.78 (2H, m), 4.42 (2H, m), and 2.29 (3H, s, CH_3); δ_C 165.89 (q), 156.92 (q), 134.93, 133.72, 132.77 (q), 132.02, 128.97, 124.77 (q), 123.41, 118.32, 117.30, 74.77, 65.47, and 16.17; *m/z* 232 (M^+, <1%), 175(14), 134(100), 106(43), 91(12), and 41(87).

(ii) (2-Allyloxy-3-methyl)benzoic acid

Allyl (2-allyloxy-3-methyl)benzoate (7 g, 0.03 mol) was added to methanol (130 ml). Aqueous sodium hydroxide (5M, 30 ml) was added, and the mixture was heated under reflux for five hours.

Methanol was removed *in vacuo*, leaving a dense white residue. Water (50 ml) was added, the solution was acidified with aqueous sulphuric acid (2M, approx. 50 ml), and extracted with ether (3x20 ml). The combined organic extracts were washed with water (50 ml), dried ($MgSO_4$) and the solvent removed *in vacuo*.

The product was obtained as a pink solid (5.71 g,

99%), m.p. 52-54°C (from n-Hexane), (Found: C, 68.6; H, 6.3. $C_{11}H_{12}O_3$ requires C, 68.75; H, 6.25%); δ_H 7.94 (1H, m), 7.42 (1H, m), 7.18 (1H, m), 6.09 (1H, m), 5.49-5.28 (2H, m), 4.49 (2H, m), and 2.35 (3H, s, CH_3), the hydroxyl signal is not apparent; δ_C 166.99 (q), 156.31 (q), 136.62, 131.73, 130.41, 124.69, 122.56 (q), 119.87, 75.85 (q), 75.67, and 16.00; *m/z* 192 (M^+, 32%), 152(13), 134(100), and 106(78).

(iii) Methyl (2-allyloxy-3-methyl)benzoate

The general method of Section D2 was employed, using methyl iodide (2.13 g, 0.015 mol), anhydrous potassium carbonate (2.07 g, 0.015 mol), and 2-allyloxy-(3-methyl)-benzoic acid (2.88 g, 0.015 mol).

The product was obtained as a yellow oil (2.78 g, 90%), b.p. 117-120°C (2.0 Torr), (Found: M^+ 206.0944; $C_{12}H_{14}O_3$ requires M^+ 206.0943); δ_H 7.62 (1H, m), 7.32 (1H, m), 7.03 (1H, m), 6.05 (1H, m), 5.42-5.20 (2H, m), 4.41 (2H, m), 3.87 (3H, s, OCH_3), and 2.29 (3H, s, CH_3); δ_C 166.76 (q), 156.84 (q), 134.88, 133.70, 132.75 (q), 128.94, 124.69 (q), 123.40, 117.33, 74.80, 51.92, and 16.15; *m/z* 206 (M^+, 13%), 175(23), 134(63), 106(67), 91(20), and 41(100).

3. Preparation of Isopropyl (2-isopropyloxy)benzoate and Isopropyl (2-isopropylthio)benzoate

The general method of Section D2 was employed using either salicylic acid or thiosalicylic acid (0.065 mol),

as appropriate, isopropyl bromide (15.99 g, 0.13 mol), and anhydrous potassium carbonate (17.97 g, 0.13 mol).

Isopropyl (2-isopropyloxy)benzoate was obtained as a clear oil (54%), b.p. 115-120°C (2.0 Torr), (Found: M^+ 222.1095. $C_{13}H_{18}O_3$ requires M^+ 222.1099); δ_H 7.68 (1H, m), 7.41 (1H, m), 6.97-6.92 (2H, m), 5.25 (1H, m), 4.57 (1H, m), and 1.34 (12H, d); *m/z* 222 (M^+, 10%), 180(29), 163(15), 120(100), and 92(47).

Isopropyl (2-isopropylthio)benzoate was obtained as a yellow oil (79%), b.p. 150-154°C (0.4 Torr), (Found: C, 65.7; H, 7.85. $C_{13}H_{18}O_2S$ requires C, 65.5; H, 7.6%); δ_H 7.79 (1H, m), 7.32-7.29 (2H, m), 7.06 (1H, m), 5.18 (1H, m), 3.42 (1H, m), and 1.27 (12H, d); δ_C 165.80 (q), 139.54 (q), 131.23, 130.29, 129.80 (q), 127.39, 123.80, 68.17, 35.03, 22.22, and 21.48; *m/z* 238 (M^+, 30%), 179(9), 136(100), and 108(12).

4. Preparation of Methyl (2-isopropylthio)benzoate

This was obtained by basic hydrolysis of isopropyl (2-isopropylthio)benzoate, followed by reaction with methyl iodide:

(i) Preparation of *2-isopropylthiobenzoic acid* using the hydrolysis method described in Section E2(ii). The product was obtained as a white solid (85%), m.p. 110-112°C (from ethanol) (Found: C, 61.5; H, 6.2. $C_{10}H_{12}O_2S$ requires C, 61.2; H, 6.1%); δ_H 8.07 (1H, m), 7.46-7.38 (2H, m), 7.21 (1H, m), 4.74 (1H, bs, *OH*),

3.51 (1H, m), and 1.36 (6H, m); δ_C 170.78 (q), 140.41 (q), 132.63, 132.26, 128.26, 128.02 (q), 124.60, 36.00, and 22.46* (* 2 peaks are coincidental); *m/z* 196 (M^+, 20%), 153(19), 136(100), and 108(31).

(ii) Preparation of *Methyl (2-isopropylthio)benzoate*

The general method described in Section D2 was employed using 2-isopropylthiobenzoic acid (1.96 g, 0.01 mol), methyl iodide (1.42 g, 0.01 mol), and anhydrous potassium carbonate (1.38 g, 0.01 mol).

The product was obtained as a yellow oil (1.62 g, 77%), b.p. 126-133°C (1.8 Torr) (Found: C, 63.1; H, 6.9. $C_{11}H_{14}O_2S$ requires C, 62.85; H, 6.65%); δ_H 7.86 (1H, m), 7.34 (2H, m), 7.14-7.06 (1H, m), 3.85 (3H, s), 3.46 (1H, m), and 9.31 (6H, d); δ_C 166.81 (q), 140.20 (q), 131.69, 130.74, 128.85 (q), 127.25, 123.89, 51.78, 35.09, 22.34; *m/z* 210 (M^+, 88%), 136(100), and 108(36).

5. Pyrolysis of Alkyl (2-allyloxy)benzoates

Methyl (2-allyloxy)benzoate

2.586 g (13 mmol), 150°C, 650°C, $1x10^{-3}$ Torr, 30 min. A yellow solid and a brown oil were deposited in the cold trap. The oil (0.45 g) was removed, and the solid was washed out with chloroform (25 ml), dried ($MgSO_4$), and the solvent was removed *in vacuo*, leaving a dark crystalline material, identified as 7-hydroxyphthalide (0.49 g, 25%), m.p. 132-134°C (from ethanol) (lit[97] 136-137°C); δ_H 7.76 (1H, bs, *OH*), 7.54 (1H, m), 6.97-6.89

(2H, m), and 5.30 (2H, s, CH_2); δ_C 172.25 (q), 156.59 (q), 146.57 (q), 136.66, 115.12, 113.07, 110.84 (q), and 70.30.

The liquid fraction was analysed by g.c. and ^1H n.m.r. spectroscopy, but no significant products could be identified.

Ethyl (2-allyloxy)benzoate

0.309 g (1.5 mmol), 120°C, 650°C, $1x10^{-3}$ Torr, 30 min.

A yellow solid and a yellow oil were obtained. The entire pyrolysate was washed out of the trap with chloroform (20 ml) and extracted with aqueous sodium carbonate (2M, 10 ml) to remove any acidic compounds. Phenolic compounds were then removed from the mother liquor following extraction with aqueous sodium hydroxide (2M, 10 ml).

The organic extract containing non-acidic compounds, was washed with water (10 ml), dried ($MgSO_4$), and the solvent removed *in vacuo*, affording a viscous brown oil (0.062 g). However, no significant products could be detected by g.c. or ^1H n.m.r. spectroscopy.

The phenolic and acidic fractions were each acidified with aqueous hydrochloric acid (2M, 10 ml), and extracted with chloroform (2x10 ml). The combined organic extracts, in each case, were washed with water (10 ml), dried ($MgSO_4$) and the solvent was removed under vacuum. Thus two compounds were obtained: 2-allyloxybenzoic acid

(0.052 g, 19%), m.p. 63-64°C (from n-hexane) (lit[126] 64-65°C); δ_H 7.47-6.73 (4H, m), 6.02 (1H, m), 5.20-5.10 (2H, m), 4.98 (1H, bs, *OH*), and 3.41 (2H, m); and a small quantity of impure *7-hydroxy-3-methylphthalide*, which was identified from its n.m.r. spectra; δ_H 7.54-6.80 (3H, m), 5.56 (1H, q, *CH*), and 1.63 (3H, d, CH_3); δ_C 171.92 (q), 156.41 (q), 151.40 (q), 136.86, 129.54 (q), 115.27, 112.73, 79.13, and 20.13.

Methyl (2-allyloxy-3-methyl)benzoate

0.308 g (1.5 mmol), 120°C, 650°C, 1×10^{-3} Torr, 30 min. A yellow solid and a red oil were obtained. The oil was removed (0.09 g), and g.c./m.s. indicates that methyl 2-hydroxy-3-methyl benzoate is present: *m/z* 166 (M^+, 47%), 134(100), and 106(86). No other significant products were identified by g.c. or ^1H n.m.r. spectroscopy.

The solid was washed from the trap with methylene chloride (15 ml), and then was washed with aqueous sodium hydroxide (2M, 10 ml) to remove any acidic compounds. The basic extract was acidified with aqueous hydrochloric acid (2M, approx.10 ml) and was then extracted with methylene chloride (15 ml). After washing with water (10 ml) and drying ($MgSO_4$), the solvent was removed *in vacuo* and a brown solid was obtained. This was identified as *7-hydroxy-6-methylphthalide* (0.048 g, 20%), m.p. 127-129°C (from ethanol) (Found: M^+ 164.0466. $C_9H_8O_3$ requires M^+ 164.0473); δ_H 7.85 (1H, bs, *OH*), 7.38 (1H, m), 6.83

(1H, m), 5.25 (2H, s, CH_2), and 2.27 (3H, s, CH_3); δ_C 172.88 (q), 154.39 (q), 143.91 (q), 137.97, 124.68 (q), 112.65, 110.24 (q), 70.27, and 14.36; *m/z* 164 (M^+, 92%), 163(14), and 135(100).

6. Pyrolysis of Isopropyl (2-isopropyloxy)benzoate and Isopropyl (2-isopropylthio)benzoate

Isopropyl (2-isopropyloxy)benzoate

0.069 g (0.31 mmol), 100°C, 750°C, 2×10^{-3} Torr, 30 min. ^{1}H n.m.r. spectroscopy revealed that no starting material was recovered, and that polymeric-type products may have been formed. G.c./m.s. (carbowax) indicated the presence of phenol *m/z* 94, as a major volatile component, but no other products could be identified.

Isopropyl (2-isopropylthio)benzoate

0.047 g (0.19 mmol), 100°C, 750°C, 5×10^{-3} Torr, 30 min. No starting material was recovered, as indicated by ^{1}H n.m.r. spectroscopy, and g.c./m.s. (carbowax). However no other compounds could be identified.

7. Pyrolysis of Methyl (2-isopropylthio)benzoate

0.176 g (0.84 mmol), 100°C, 750°C, 5×10^{-3} Torr, 60 min: A crystalline solid and a yellow oil were obtained. The entire pyrolysate was washed out of the trap with

chloroform (15 ml) and the acidic and non-acidic compounds were separated, as in Section 5(b).

The non-acidic fraction afforded a thick yellow oil (0.18 g). Analysis by ^{1}H n.m.r. spectroscopy and g.c. indicated that polymeric material may have been formed.

A yellow crystalline solid was obtained from the acidic fraction. This was identified as 7-mercaptophthalide (0.025 g, 18%), m.p. 114-116°C (from ethanol) (Found: C, 57.8; H, 3.7. $C_8H_6O_2S$ requires C, 57.8; H, 3.6%); δ_H 7.46 (1H, m), 7.27 (1H, m), 7.15 (1H, m), 6.25 (1H, s, *SH*), and 5.24 (2H, s, CH_2); δ_C 133.87, 128.31, 117.51, and 68.61. (No quaternaries are apparent at this concentration); *m/z* 166 (M^+, 100), 137(93), and 109(36).

F The Generation and Cyclisation of (2-Aryloxycarbonyl)-phenoxyl and (2-Aryloxycarbonyl)thiophenoxyl Radicals

1. Preparation of Radical Precursors

Two methods have been employed:

(a) Method I

This involves the preparation of the appropriate phenyl (2-hydroxy)benzoate or phenyl (2-thio)benzoate, followed by formation of the *O*- or *S*-allyl derivative.

(i) Preparation of phenyl benzoates

Salicyclic acid or thiosalicyclic acid (0.127 mol) was melted with the appropriately-substituted phenol (0.127 mol) at 135°C. Phosphoryl chloride (7 g, 0.046 mol) was then added gradually and the temperature was moderated until the evolution of hydrogen chloride had ceased. The reaction mixture was cooled in ice, water (250 ml) was added, and the product was deposited upon trituration. The reaction mixture was then washed with aqueous sodium carbonate (4M, 50 ml) to remove any unreacted acid.

Some products were obtained as oils, and these were then extracted with methylene chloride (3x50 ml), washed with water (2x50 ml), dried ($MgSO_4$), and the solvent removed *in vacuo*. These compounds were then purified by distillation. The following compounds were prepared:

Phenyl (2-mercapto)benzoate (60%), m.p. 82-85°C (from ethanol) (lit[127] 91°C); δ_H 8.27 (1H, d), 7.49-7.20 (8H, m),

and 4.47 (1H, s, *SH*); *m/z* 230 (M^+, 89%), 137(100), and 109(82).

2-Methylphenyl (2-mercapto)benzoate (35%), m.p. 47-50°C (from ethanol); δ_H 7.41-7.11 (8H, m), 4.82 (1H, s, *SH*), and 2.24 (3H, s); *m/z* 244 (M^+, 100%), 137(65) and 108(22).

3-Methylphenyl (2-mercapto)benzoate (31%), m.p. 102-104°C (from ethanol); δ_H 7.31-7.00 (8H, m), 4.76 (1H, s, *SH*), and 2.41 (3H, s); *m/z* 244 (M^+, 100%), 137(84), and 108(31).

4-Methylphenyl (2-mercapto)benzoate (44%), m.p. 50-53°C (from ethanol); δ_H 8.25 (1H, d), 7.39-7.05 (7H, m), 4.78 (1H, s, *SH*), and 2.37 (3H, s); *m/z* 244 (M^+, 85%), 137(85), and 108(100).

2-Chlorophenyl (2-mercapto)benzoate (24%), m.p. 49-51°C (from ethanol); δ_H 8.52 (1H, m), 7.75-7.30 (7H, m), and 4.80 (1H, s, *SH*).

4-Chlorophenyl (2-mercapto)benzoate (37%), b.p. 166-168°C (0.1 Torr); δ_H 8.23 (1H, m), 7.45-7.08 (7H, m), and 4.67 (1H, s, *SH*); *m/z* 264 (M^+, 9%), 137(100), 128(18), and 109(26).

2-Methylphenyl (2-hydroxy)benzoate (82%), m.p. 32-33°C (from methanol) (lit[128] 35°C); δ_H 10.59 (1H, bs, *OH*), 8.13 (1H, m), 7.51-7.04 (7H, m), and 2.27 (3H, s); *m/z* 228 (M^+, 33%), 121(100), 108(32), and 93(25).

3-Methylphenyl (2-hydroxy)benzoate (44%), m.p. 72-74°C (from ethanol) (lit[128] 74°C); δ_H 10.51 (1H, bs, *OH*), 8.07 (1H, m), 7.64-6.80 (7H, m), and 2.39 (3H, s);

m/z 228 (M^+, 58%), 121(100), 107(28), and 93(35).

4-Methylphenyl (2-hydroxy)benzoate (46%), m.p. 38-40°C (from methanol) (lit.[128] 39°C); δ_H 10.56 (1H, bs, *OH*), 8.09 (1H, m), 7.27-6.97 (7H, m), and 2.39 (3H, s); *m/z* 228 (M^+, 27%), 121(100), 107(24), and 93(20).

2-Chlorophenyl (2-hydroxy)benzoate (80%), m.p. 53-54°C (from ethanol) (lit.[129] 55°C); δ_H 10.25 (1H, bs, *OH*), 8.09 (1H, m), and 7.66-6.87 (7H, m).

4-Chlorophenyl (2-hydroxy)benzoate (67%), m.p. 62-64°C (from ethanol) (lit.[129] 69.5-70.5°C); δ_H 10.41 (1H, bs, *OH*), 8.05 (1H, m), and 7.58-6.93 (7H, m).

2,6-Dichlorophenyl (2-hydroxy)benzoate (83%), m.p. 86-88°C (from ethanol) (lit.[130] 110°C); δ_H 10.13 (1H, bs, *OH*), 8.15 (1H, m), and 7.62-6.96 (6H, m). Despite the low melting point, ^{1}H n.m.r. spectroscopy has indicated that the sample was quite pure.

2-Methoxyphenyl (2-hydroxy)benzoate (66%), m.p. 62-64°C (from ethanol) (lit.[131] 65°C); δ_H 9.50 (1H, bs, *OH*), 8.15 (1H, m), 7.65-6.80 (7H, m), and 3.80 (3H, s); *m/z* 244 (M^+, 12%), 121(100), and 93(9).

4-Methoxyphenyl (2-hydroxy)benzoate (83%), m.p. 87-89°C (from ethanol) (lit.[132] 91-92°C); δ_H 8.12-8.01 (1H, m), 7.63-6.84 (7H, m), and 3.81 (3H, s).

4-Nitrophenyl (2-hydroxy)benzoate (80%), m.p. 149-151°C (from 1,4-dioxan) (lit.[129] 151.5-151.9°C); *m/z* 259 (M^+, 10%), 212(10), 121(100), and 93(10).

Phenyl (2-hydroxy-4-methyl)benzoate (96%), m.p. 43-45°C (from ethanol) (lit.[133] 47°C); δ_H 7.95 (1H, m), 7.49-7.23 (5H, m), 6.86-6.77 (2H, m), and 2.39 (3H, s).

(ii) Preparation of Phenyl (2-allylthio)benzoates and Phenyl (2-allyloxy)benzoates

The following *S*- and *O*-allyl compounds were prepared from the appropriate (2-mercapto)benzoate or (2-hydroxy)-benzoate, respectively, by the method previously described for the corresponding benzamide system (Section D.2):

Phenyl (2-allylthio)benzoate (89%), m.p. 60-62°C (from ethanol) (Found: C, 69.4; H, 5.2. $C_{16}H_{14}O_2S.0.3H_2O$ requires C, 69.5; H, 5.3%); δ_H 8.19 (1H, m), 7.54-7.19 (7H, m), 6.00 (1H, m), 5.39-5.16 (2H, m), and 3.65 (2H, m); δ_C 164.54 (q), 150.69 (q), 141.74 (q), 132.46, 131.41, 129.16, 126.52, 125.59 (q), 124.05, 121.53, 118.31, 77.52, 76.88, and 35.34; *m/z* 270 (M^+, 1.5%), 117(100), 149(18), and 108(26).

2-Methylphenyl (2-allylthio)benzoate (80%), m.p. 63-65°C (from ethanol) (Found: C, 71.7; H, 5.65. $C_{17}H_{16}O_2S$ requires C, 71.8; H, 5.6%); δ_H 7.51-7.12 (8H, m), 5.90 (1H, m), 5.38-5.16 (2H, m), 3.63 (2H, m), and 2.25 (3H, s); δ_C 164.80 (q), 150.78 (q), 141.80 (q), 139.46 (q), 132.66, 132.44, 131.52, 128.99, 127.82 (q), 126.72, 126.51, 124.19, 122.23, 118.57, 118.39, 35.54, and 21.15; *m/z* 284 (M^+, 14%), 177 (100), 149(18), and 108(20).

3-Methylphenyl (2-allylthio)benzoate (52%), m.p. 41-43°C (from ethanol) (Found: C, 71.0; H, 5.6. $C_{17}H_{16}O_2S.0.4H_2O$ requires C, 71.05; H, 5.75%); δ_H 8.18 (1H, m), 7.55-7.01 (7H, m), 5.92 (1H, m), 5.38-5.16 (2H, m), 3.63 (2H, m) and 2.44 (3H, s); δ_C 164.73 (q), 150.51 (q), 142.13 (q), 139.40 (q), 132.56, 132.40, 131.59, 128.95, 126.88 (q),

126.49, 126.08, 123.93, 122.19, 118.51, 35.17, and 21.15 (two carbons are coincidental at 118.51); *m/z* 284 (M^+, 14%), 177(100), 149(36), and 108(35).

4-Methylphenyl (2-allylthio)benzoate (72%), m.p. 28-30°C (from ethanol) (Found: C, 71.8; H, 5.6. $C_{17}H_{16}O_2S$ requires C, 71.8; H, 5.6%); δ_H 8.23 (1H, m), 7.51-7.28 (2H, m), 7.26-7.10 (5H, m), 5.90 (1H, m), 5.45-5.18 (2H, m), 3.70-3.63 (2H, m), and 2.45 (3H, s); δ_C 164.76 (q), 148.45 (q), 141.71 (q), 135.19 (q), 132.51, 132.36, 131.41, 129.68, 127.54 (q), 126.47, 124.03, 121.20, 118.32, 35.34, and 20.62; *m/z* 284 (M^+, 11%), 177(100), 149(26), and 108(40).

2-Chlorophenyl (2-allylthio)benzoate (64%), m.p. 34-36°C (from ethanol) (Found: C, 62.8; H, 4.2. $C_{16}H_{13}ClO_2S$ requires C, 63.0; H, 4.3%); δ_H 8.30 (1H, m), 7.55-7.16 (7H, m), 5.92 (1H, m), 5.40-5.16 (2H, m), and 3.64 (2H, m); δ_C 163.48 (q), 147.00 (q), 142.43 (q), 135.47 (q), 132.77, 132.46, 131.00 (q), 130.80, 127.52, 126.92, 126.81, 126.48, 124.12, 123.91, 118.44, and 35.32; *m/z* 306 (M^+, 2%), 304 (M^+, 6%), 177(100), 149(17), and 108(26).

4-Chlorophenyl (2-allylthio)benzoate (75%), m.p. 45-47°C (from ethanol) (Found: C, 62.6; H, 4.25. $C_{16}H_{13}ClO_2S$ requires C, 63.05; H, 4.25%); δ_H 8.16 (1H, m), 7.53-7.13 (7H, m), 5.92 (1H, m), 5.38-5.16 (2H, m), and 3.62 (2H, m); δ_C 164.32 (q), 149.05 (q), 142.41 (q), 132.82, 132.28, 131.66, 131.05 (q), 129.29, 126.33 (q), 126.10, 123.98, 123.02, 118.65 and 35.16; *m/z* 306 (M^+, 1%), 304 (M^+, 1.2%), 177(100), 149(23), and 136(39).

Phenyl (2-allyloxy)benzoate (83%), b.p. 137-140°C (0.4 Torr) (Found: C, 75.3; H, 5.45. $C_{16}H_{14}O_3$ requires C, 75.6; H, 5.5%); δ_H 8.09 (1H, m), 7.68-6.95 (8H, m), 6.06 (1H, m), 5.66-5.23 (2H, m), and 4.64 (2H, m); δ_C 163.95 (q), 158.22 (q), 150.74 (q), 133.58, 132.19, 131.58, 128.90, 125.16, 121.36, 120.01, 119.42 (q), 116.83, 113.35, and 68.94; *m/z* 254 (M^+, 4%), 161(100), 133(13), and 92(7).

2-Methylphenyl (2-allyloxy)benzoate (80%), m.p. 39-41°C (from ethanol) (Found: C, 76.1; H, 6.0. $C_{17}H_{16}O_3$ requires C, 76.1; H, 6.0%); δ_H 8.05 (1H, m), 7.57-7.01 (7H, m), 6.05 (1H, m), 5.58-5.26 (2H, m), 4.67 (2H, m), and 2.29 (3H, s); δ_C 164.14 (q), 158.48 (q), 149.58 (q), 133.71 (q), 132.48, 131.86, 130.89, 130.24, 126.65, 125.67, 121.94, 120.32, 119.88 (q), 117.38, 113.62, 69.41, and 16.15; *m/z* 268 (M^+, 1%), 228(19), 161(27), 121(100), and 108(23).

3-Methylphenyl (2-allyloxy)benzoate (84%), b.p. 136-140°C (0.3 Torr) (Found: C, 76.3; H, 6.0. $C_{17}H_{16}O_3$ requires C, 76.1; H, 6.0%); δ_H 8.02 (1H, m), 7.99-7.01 (7H, m), 6.09 (1H, m), 5.59-5.24 (2H, m), 4.66 (2H, m), and 2.27 (3H, s); δ_C 164.52 (q), 158.62 (q), 150.96 (q), 139.36 (q), 133.82, 132.54, 131.99, 129.23, 128.95, 126.32, 120.84 (q), 120.37, 119.91, 118.62, 115.96, 69.47, and 21.13; *m/z* 268 (M^+, <1%), 161(100), and 133(12)

4-Methylphenyl (2-allyloxy)benzoate (83%), b.p. 163-165°C (0.3 Torr) (Found: C, 76.2; H, 6.0. $C_{17}H_{16}O_3$ requires C, 76.1; H, 6.0%); δ_H 8.03 (1H, m), 7.55-7.01 (7H, m), 6.05 (1H, m), 5.60-5.25 (2H, m), 4.65 (2H, m), and 2.37

(3H, s); δ_C 164.62 (q), 158.56 (q), 148.68 (q), 135.11 (q), 133.84, 132.44, 132.04, 129.76, 121.36, 120.33, 119.75 (q), 117.34, 113.57, 69.36, and 20.73; *m/z* 268 (M^+, 1%), 228(8), 121(100), and 93(10).

Phenyl (2-allyloxy-4-methyl)benzoate (90%), m.p. 51-53°C (from ethanol) (Found: C, 76.2; H, 6.1. $C_{17}H_{16}O_3$ requires C, 76.1; H, 6.0%); δ_H 7.95 (1H, m), 7.46-6.83 (7H, m), 6.04 (1H, m), 5.60-5.25 (2H, m), 4.64 (2H, m), and 2.44 (3H, s); δ_C 164.14 (q), 158.88 (q), 151.07 (q), 145.04 (q), 138.56, 138.15, 129.12, 125.38, 121.70, 121.23, 117.16, 116.76 (q), 114.46, 69.41, and 21.70; *m/z* 268 (M^+, 7%), 175(100), 147(26), 119(32), 91(18), and 41(56).

2-Chlorophenyl (2-allyloxy)benzoate (84%), b.p. 193-198°C (0.8 Torr) (Found: C, 66.9; H, 4.65. $C_{16}H_{13}ClO_3$ requires C, 66.6; H, 4.5%); δ_H 8.13 (1H, m), 7.57-7.45 (2H, m), 7.36-7.16 (3H, m), 7.10-6.94 (2H, m), 6.09 (1H, m), 5.59-5.24 (2H, m), and 4.65 (2H, m); δ_C 162.92 (q), 158.91 (q), 147.14 (q), 134.30, 132.56, 132.35, 130.12, 127.54, 126.99 (q), 126.71, 123.95, 120.30, 118.59 (q), 117.39, 113.53, and 69.32; *m/z* 288 (M^+, 5%), and 161(100).

4-Chlorophenyl (2-allyloxy)benzoate (86%), m.p. 43-45°C (from ethanol) (Found: C, 66.0; H, 4.4. $C_{16}H_{13}ClO_3$ requires C, 66.6; H, 4.5%); δ_H 8.01 (2H, m), 7.56-6.81 (7H, m), 6.08 (1H, m), 5.58-5.25 (2H, m), and 4.65 (2H, m); δ_C 164.00 (q), 158.70 (q), 149.50 (q), 134.05, 132.43, 132.01, 130.85 (q), 129.23, 123.02, 120.38, 119.40 (q), 117.40, 113.72, and 69.47; *m/z* 290 (M^+, <1%), 288 (M^+, <1%), 161(100), 133(10), and 92(10).

2,6-Dichlorophenyl (2-allyloxy)benzoate (91%), b.p. 160-165°C (0.4 Torr) (Found: C, 59.6; H, 3.8. $C_{16}H_{12}Cl_2O_3$ requires C, 59.45; H, 3.7%); δ_H 8.16 (1H, m), 7.58-6.98 (6H, m), 6.13 (1H, m), 5.58-5.23 (2H, m), and 4.65 (2H, m); δ_C (D.E.P.T.) 134.55, 132.39, 128.69, 128.44, 126.84, 120.29, 117.34, 113.63, and 69.39 (2 peaks are coincidental at δ_C 128.44); *m/z* 322 (M^+, 4%), 161(100), and 133(48).

2-Methoxyphenyl (2-allyloxy)benzoate (78%), m.p. 38-41°C (from ethanol) (Found: C, 72.1; H, 5.8. $C_{17}H_{16}O_4$ requires C, 71.8; H, 5.65%); δ_H 8.07 (1H, m), 7.54-6.90 (7H, m), 6.07 (1H, m), 5.59-5.22 (2H, m), 4.64 (2H, m), and 3.81 (3H, s); δ_C 163.74 (q), 158.74 (q), 151.46 (q), 140.22 (q), 133.71, 132.71, 132.26, 126.56, 123.07, 120.70, 120.41, 119.98 (q), 117.24, 113.92, 112.62, 69.54, and 55.86; *m/z* 284 (M^+, 15%), and 161(100).

4-Methoxyphenyl (2-allyloxy)benzoate (94%), m.p. 47-49°C (from ethanol) (Found: C, 72.1; H, 5.7. $C_{17}H_{16}O_4$ requires C, 71.8; H, 5.65%); δ_H 8.01 (1H, m), 7.97 (1H, m), 7.50-6.89 (6H, m), 6.04 (1H, m), 5.57-5.23 (2H, m), 4.63 (2H, m), and 3.80 (3H, s); δ_C 164.69 (q), 158.43 (q), 156.95 (q), 144.26 (q), 133.84, 132.37, 131.96, 122.35, 120.21, 119.44 (q), 117.25, 114.21, 113.37, 69.16, and 55.33; *m/z* 284 (M^+, 12%), 161(100), 132(30), and 123(15).

(iii) Base-promoted reaction of 4-Nitrophenyl (2-hydroxy)-benzoate and Allyl bromide

Under the basic conditions employed in the general alkylation procedure (Section D.2) this benzoate can undergo

Smile's rearrangement[99], and hence the rearranged product is subsequently alkylated. Thus *Allyl 2-(4-nitrophenoxy)benzoate* was obtained as a brown solid (72%), m.p. 63-65°C (from ethanol) (Found: C, 64.0; H, 4.35; N, 4.7. $C_{16}H_{13}NO_5$ requires C, 64.2; H, 4.35; N, 4.7%); δ_H 8.16 (2H, m), 8.02 (2H, m), 7.60 (1H, m), 7.35 (1H, m), 7.13 (1H, m), 6.91 (2H, m), 5.78 (1H, m), 5.37-5.20 (2H, m), and 4.62 (2H, m); δ_C 164.14 (q), 163.53 (q), 153.37 (q), 142.32 (q), 134.22, 132.34, 131.40, 125.74, 124.01 (q), 123.00, 118.47, 116.07, and 65.73 (2 peaks are coincidental at δ_C 125.74); *m/z* 299 (M^+, 48%), 242(46), 196(100), and 168(27).

(b) Method II

This involves (i) the preparation of either 2-allyloxybenzoic acid or 2-isopropylthiobenzoic acid, and (ii) the conversion of the appropriate acid to the required ester.

(i) Preparation of 2-Allyloxybenzoic acid

Basic hydrolysis of methyl (2-allyloxy)benzoate (prepared in Section E.1), by the method described in Section E.2(ii), gave 2-allyloxybenzoic acid as a yellow solid (81%), m.p. 62-64°C (from n-hexane) (lit.[126] 64-65°C); δ_H 8.09 (1H, m), 7.49 (1H, m), 7.10-6.99 (2H, m), 6.04 (1H, m), 5.50-5.33 (2H, m), and 4.74 (2H, m).

The preparation of 2-isopropylthiobenzoic acid is described in Section E.4(i).

(ii) Preparation of Phenyl (2-allyloxy)benzoates and Phenyl (2-isopropylthio)benzoates

2-Allyloxybenzoic acid (3.56 g, 0.02 mol) and thionyl chloride (2.86 g, 0.024 mol) were heated under reflux, on a water bath, for thirty minutes. Excess thionyl chloride was removed *in vacuo* (using a water pump).

The acid chloride thus formed was dissolved in methylene chloride (25 ml), and 4-dimethylaminopyridine (D.M.A.P.) (0.02 g, 0.0002 mol) was added, followed by the addition of the appropriate phenol (0.02 mol). Triethylamine (2.02 g, 0.02 mol) in methylene chloride (25 ml) was then added dropwise and the solution was stirred for three hours.

The dense white precipitate of triethylamine hydrochloride was then removed by filtration, and the solution was washed with water (3x15 ml), dried ($MgSO_4$) and the solvent removed *in vacuo*.

The following compounds were prepared by this method *4-Nitrophenyl (2-allyloxy)benzoate* (70%) m.p. 62-64°C (from ethanol) (Found: C, 64.0; H, 4.4; N, 4.7. $C_{16}H_{13}NO_5$ requires C, 64.2; H, 4.35; N, 4.7%); δ_H 8.11 (1H, m), 7.55 (1H, m), 7.17-7.05 (2H, m), 6.99-6.93 (3H, m), 6.08 (1H, m), 5.52-5.39 (2H, m), and 4.80 (2H, m); δ_C 167.20 (q), 162.38 (q), 157.44 (q), 140.90 (q), 135.49, 133.47, 130.59, 125.96, 122.37, 120.52, 117.14 (q), 115.64, 113.17, and 70.86; *m/z* 299 (M^+, 0.3%), 161(100), 133(12), and 41(20). *4-Cyanophenyl (2-allyloxy)benzoate* (89%) m.p. 43-45°C (from ethanol) (Found: C, 73.1; H, 4.6; N, 5.15. $C_{17}H_{13}NO_3$ requires C, 73.1; H, 4.7; N, 5.0%); δ_H 7.99 (1H,

m), 7.79-6.90 (7H, m), 6.04 (1H, m), 5.61-5.17 (2H, m), and 4.65 (2H, m); δ_C 163.26 (q), 158.89 (q), 154.23 (q), 134.63, 133.42, 132.17, 122.81, 120.34, 118.24 (q), 118.12 (q), 117.51, 113.52, 109.28 (q), and 69.28; *m/z* 279 (M^+, trace), 161(100), 133(35), and 92(27).

3-Pyridyl (2-allyloxy)benzoate (87%) b.p. 173-178°C (0.8 Torr) (Found: M^+ 255.0901. $C_{15}H_{13}NO_3$ requires M^+ 255.0895); δ_H 8.53-8.45 (2H, m), 8.01 (1H, m), 7.62-7.25 (3H, m), 7.06-6.97 (2H, m), 5.99 (1H, m), 5.54-5.22 (2H, m), and 4.62 (2H, m); δ_C 167.98 (q), 158.91 (q), 156.97, 146.03 (q), 143.04 (q), 139.86, 137.90, 136.32, 133.68, 132.46, 124.87, 121.51, 119.18, 113.06, and 70.15; *m/z* 255 (M^+, <1%), 161(100), 133(11), and 41(19).

1-Naphthyl (2-allyloxy)benzoate (68%) m.p. 59-61°C (from ethanol) (Found: C, 78.6; H, 5.3. $C_{20}H_{16}O_3$ requires C, 78.9; H, 5.25%); δ_H 8.18-7.05 (11H, m), 6.10 (1H, m), 5.58-5.24 (2H, m), and 4.72 (2H, m); δ_C 164.69 (q), 158.66 (q), 146.89 (q), 134.57 (q), 134.15, 132.39, 132.31, 127.79, 126.95 (q), 126.23, 125.78, 125.36, 121.71, 120.45, 119.43 (q), 118.20, 117.75, 113.47, and 69.47 (* two peaks are coincidental at 126.23); *m/z* 304 (M^+, 22%), 161(100), 133(75), and 105(56).

2-Naphthyl (2-allyloxy)benzoate (76%) m.p. 49-51°C (from ethanol) (Found: C, 79.1; H, 5.2. $C_{20}H_{16}O_3$ requires C, 78.9; H, 5.25%); δ_H 8.11-7.01 (11H, m), 6.08 (1H, m), 5.60-5.25 (2H, m), and 4.68 (2H, m); δ_C 164.52 (q), 158.70 (q), 148.60 (q), 134.03, 133.72 (q), 132.42, 132.15, 131.33 (q), 129.19, 127.61, 127.54, 126.30, 125.44,

121.34, 120.37, 119.55 (q), 118.62, 117.42, 113.60, and 69.38; *m/z* 304 (M^+, 15%), 161(100), and 144(30).

8-Quinolinyl (2-allyloxy)benzoate (91%) m.p. 124-126°C (from ethanol) (Found: C, 74.9; H, 5.0; N, 4.5. $C_{19}H_{15}NO_3$ requires C, 74.75; H, 4.9; N, 4.6%); δ_H 8.89 (1H, m), 8.30-8.17 (2H, m), 7.73 (1H, m), 7.58-7.37 (4H, m), 7.13-7.01 (2H, m), 6.07 (1H, m), 5.56-5.20 (2H, m), and 4.68 (2H, m); δ_C 164.23 (q), 158.95 (q), 150.31, 147.65 (q), 141.43 (q), 135.69, 133.95, 132.74, 132.59, 129.41 (q), 126.05, 125.58, 121.59, 121.46, 120.40, 119.52 (q), 117.20, 113.70, and 69.46; *m/z* 305 (M^+, 17%), 161(100), 133(36), and 92(41).

The following compounds were prepared from 2-isopropylthiobenzoic acid, by the same method:

Phenyl (2-isopropylthio)benzoate (75%) m.p. 57-59°C (from ethanol) (Found: C, 68.9; H, 5.4. $C_{16}H_{16}O_2S.0.4H_2O$ requires C, 68.8; H, 6.0%); δ_H 8.14 (1H, m), 7.58-7.19 (8H, m), 3.55 (1H, m), and 1.38 (6H, m); δ_C 164.89 (q), 150.73 (q), 141.23 (q), 132.31, 131.33, 129.23, 127.89, 125.98 (q), 125.67, 124.25, 121.65, 35.56, and 22.52; *m/z* 272 (M^+, 13%), 179(100), 137(64), 109(22), and 43(30).

2,6-Dichlorophenyl (2-isopropylthio)benzoate (73%), m.p. 65-67°C (from ethanol) (Found: C, 56.7; H, 4.2. $C_{16}H_{14}Cl_2O_2S$ requires C, 56.3; H, 4.1%); δ_H 8.33 (1H, m), 7.53-7.11 (6H, m), 3.57 (1H, m), and 1.38 (6H, m); δ_C 162.27 (q), 143.99 (q), 142.80 (q), 132.98, 132.09, 129.08 (q), 128.45, 127.40, 127.00, 126.03 (q), 124.05, 35.26, and

22.46; *m/z* 340 (M^+, 5%), 179(100), 161(45), 137(80), 136(22), and 43(35).

(iii) Preparation of *Allyl (2-allylthio)benzoate*

Thiosalicylic acid (6.17 g, 0.04 mol), allyl bromide (14.52 g, 0.12 mol), and anhydrous potassium carbonate (16.59 g, 0.12 mol) were reacted as described in Section D.2. *Allyl (2-allylthio)benzoate* was obtained as a clear oil (8.57 g, 87%), b.p. 155-160°C (0.4 Torr), δ_H 7.95 (1H, m), 7.40-7.28 (2H, m), 7.12 (1H, m), 6.09-5.83 (2H, m), 5.43-5.12 (4H, m), 4.80 (2H, m), and 3.57 (2H, m).

(iv) Reaction of Allyl (2-allylthio)benzoate and Sodium hydroxide

Crude allyl (2-allylthio)benzoate (5.5 g, 0.024 mol) was reacted with aqueous sodium hydroxide (5M, 30 ml) in methanol (100 ml) by the method described in Section E.2(ii). Work-up afforded 2-(2-propenylthio)benzoic acid (3.87 g, 85%), m.p. 143-145°C (from ethyl acetate) (lit.[101] 144-146°C); δ_H 9.60 (1H, bs, *OH*), 8.09 (1H, m), 7.50-7.10 (3H, m), 6.30-6.12 (2H, m), and 1.90 (3H, d, CH_3); *m/z* 194 (M^+, 100%), and 153(32).

O-Alkylation of this compound under standard basic conditions, using allyl bromide (Section D.2) gave *allyl (2-propenylthio)benzoate* (86%), b.p. 155-160°C (0.4 Torr); δ_H 7.97 (1H, m), 7.42-7.02 (3H, m), 6.29-5.80 (3H, m), 5.51-5.16 (2H, m), 4.80 (2H, m), and 1.84 (3H, d, CH_3).

(v) Preparation of *(2-allyloxy)biphenyl*

2-Hydroxybiphenyl (5.11 g, 0.03 mol) was reacted with allyl bromide, under basic conditions, by the method described in Section D.2, to give *(2-allyloxy)-biphenyl* (5.66 g, 90%) b.p. 125-128°C (1.0 Torr) (Found: C, 86.2; H, 6.9. $C_{15}H_{14}O$ requires C, 85.7; H, 6.7%); δ_H 7.65-7.00 (9H, m), 6.02 (1H, m), 5.43-5.21 (2H, m), and 4.58 (2H, m); δ_C 155.41 (q), 138.46 (q), 133.23, 131.08 (q), 130.86, 129.51, 128.38, 127.78, 126.73, 121.05, 116.68, 112.94, and 69.05; *m/z* 210 (M^+, 89%), 169(100), 141(53), and 115(59).

2. Pyrolysis Experiments

(a) General work-up procedure

Where pyrolysis is carried out on a preparative scale (i.e. >100 mg), a general work-up procedure is employed. This involves dissolving the entire pyrolysate in methylene chloride (∿30 ml) and then washing this solution with aqueous sodium hydroxide (2M, 15 ml) to remove any acidic compounds. The neutral fraction is then washed with water (2x15 ml), dried ($MgSO_4$) and the solvent removed *in vacuo* to give the non-acidic components. The basic solution is then acidified with aqueous hydrochloric acid (2M), and extracted with methylene chloride (2x10 ml). The combined organic fractions are then washed with water (20 ml), dried ($MgSO_4$) and the solvent

removed *in vacuo*, thus yielding the acidic components.

(b) Pyrolysis of phenyl (2-allylthio)benzoates

Phenyl (2-allylthio)benzoate

1.037 g (4 mmol), 150°C, 650°C, $1x10^{-3}$ Torr, 75 min. Dibenzothiophene was obtained as a white solid (0.62 g, 88%), m.p. 96-99°C (from ethanol), mixed m.p. 96-98°C (lit.[134] 98-100°C); δ_C 139.21 (q), 135.32 (q), 126.45, 124.11, 122.55, and 121.34.

2-Methylphenyl (2-allylthio)benzoate

0.057 g (0.2 mmol), 130°C, 650°C, $1x10^{-3}$ Torr, 40 min. G.c./m.s. indicated that *o*-cresol *m/z* 108 (M^+, 100%), dibenzothiophene *m/z* 184 (M^+, 100%), and 4-methyldibenzothiophene *m/z* 198 (M^+, 100%) are present.

Thioxanthene may also be formed, as suggested by ^{1}H n.m.r. spectroscopy: δ_H 3.87 (2H, s, CH_2), which compares well with the authentic spectrum δ_H 3.90[135]; and by the ^{13}C n.m.r. (D.E.P.T.) spectrum, which reveals a methylene peak at δ_C 39.07 compared with δ_C 39.08 for the authentic sample[135].

Pyrolysis was repeated on a preparative scale: 0.653 g (2.3 mmol), 150°C, 650°C, $1x10^{-3}$ Torr, 75 min. The general work-up procedure was employed, and the non-acidic compound was then chromatographed on a silica flash column, using ether/hexane as eluant. The following components were isolated: 4-methyldibenzothiophene 0.18 g (40%)

m.p. 60-63°C (from ethanol) (lit.[136] 65°C) δ_H 8.03 (1H, m), 7.52-7.22 (6H, m), and 2.62 (3H, s, CH_3), which was contaminated with a trace of thioxanthene, δ_H 3.88; and dibenzothiophene 0.04 g (9.3%) m.p. 94-96°C (from ethanol) (lit.[134] 98-100°C).

3-Methylphenyl (2-allylthio)benzoate

0.053 g (0.19 mmol), 120°C, 650°C, $1x10^{-3}$ Torr, 45 min. The entire pyrolysate was analysed by g.c./m.s. and ^1H n.m.r. spectroscopy. G.c./m.s. reveals a small peak *m/z* 108 (M^+, 100%), identified as *m*-cresol and a large broad peak, partially resolved into two, *m/z* 198 (M^+, 100%) indicating the presence of two isomers. The ^1H n.m.r. spectrum shows two methyl peaks, further suggesting the formation of 1-methyldibenzothiophene* and 3-methyldibenzothiophene: δ_H 8.41-8.36 (2H, m), 8.14-7.22 (12H, m), 2.93 (3H, *s*, CH_3)* and 2.52 (3H, s, CH_3). The yield of each isomer was calculated, using a 5 µl cyclohexane standard, as 32% and 23%, respectively.

Pyrolysis was repeated on a preparative scale, 0.14 g (0.5 mmol), 120°C, 650°C, $5x10^{-3}$ Torr, 50 min; followed by the general work-up, thus isolating the two isomers with a combined yield of 0.07 g (58%).

4-Methylphenyl (2-allylthio)benzoate

3.21 g (11 mmol), 180°C, 650°C, $1x10^{-3}$ Torr, 120 min. 2-Methyldibenzothiophene (1.96 g, 90%) was obtained using the general work-up procedure; m.p. 83-86°C (from ethanol)

lit.[137] 85-86°C); δ_H 8.23-7.20 (7H, m) and 2.53 (3H, s, CH_3); δ_C 139.78 (q), 136.38 (q), 135.63 (q), 135.35 (q), 133.91 (q), 127.99, 126.28, 123.96, 122.61, 122.21, 121.55, 121.23, and 21.16; *m/z* 198 (M^+, 100%).

2-Chlorophenyl (2-allylthio)benzoate

0.070 g (0.23 mmol), 170°C, 650°C, $1x10^{-2}$ Torr, 40 min. G.c./m.s. indicated that dibenzothiophene *m/z* 184 (M^+, 100%), 4-chlorodibenzothiophene *m/z* 218 (M^+, 100%) are present.

Pyrolysis was repeated on a preparative scale, 0.447 g (1.46 mmol), 150°C, 650°C, $1x10^{-3}$ Torr, 95 min. Following a general work-up the pyrolysate was chromatographed on a silica flash column, using ether/hexane as eluant. Thus 4-chlorodibenzothiophene 0.041 g (13%) m.p. 120-122°C (from ethanol) (lit.[138] 122°C),) and dibenzothiophene 0.061 g (23%) m.p. 95-96°C (from ethanol) (lit[134] 98-100°C) were isolated.

4-Chlorophenyl (2-allylthio)benzoate

1.013 g (3.9 mmol), 160°C, 650°C, $1x10^{-3}$ Torr, 60 min. The general work-up removed a small trace of *p*-chlorophenol, thus isolating 2-chlorodibenzothiophene (0.81 g, 94%) m.p. 122-124°C (from ethanol) (lit.[139] 125-126°C), δ_H 8.09-7.37 (7H, m); δ_C 140.13 (q), 137.45 (q), 136.83 (q), 134.47 (q), 130.59 (q), 127.20, 126.79, 124.49, 123.60, 122.77, 121.63, and 121.35; *m/z* 220 (M^+, 33%), and 218 (M^+, 100%).

(c) Pyrolysis of phenyl (2-isopropylthio)benzoates

Phenyl (2-isopropylthio)benzoate

1.004 g (3.7 mmol), 170°C, 750°C, $1x10^{-3}$ Torr, 35 min. After work-up, dibenzothiophene (0.51 g, 73%) was isolated, m.p. 96-98°C (from ethanol) (lit.[134] 98-100°C).

2,6-Dichlorophenyl (2-isopropylthio)benzoate

0.038 g (0.1 mmol), 150°C, 750°C, $1x10^{-3}$ Torr, 60 min. A white solid was obtained. One peak is apparent from the g.c. of the pyrolysate, and has been identified as 4-chlorodibenzothiophene by matching with the g.c. of the pyrolysate of 2-chlorophenyl (2-allylthio)benzoate.

(d) Pyrolysis of phenyl (2-allyloxy)benzoates

Phenyl (2-allyloxy)benzoate

1.106 g (5 mmol), 160°C, 650°C, $5x10^{-3}$ Torr, 40 min. General work-up procedure produced phenol 0.03 g (6%), and dibenzofuran 0.52 g (62%) m.p. 79-81°C (from ethanol) (lit.[134] 83-84°C); δ_C 156.02 (q), 126.97, 124.06 (q), 122.52, 120.49, and 111.50.

2-Methylphenyl (2-allyloxy)benzoate

0.048 g (0.18 mmol), 150°C, 650°C, $1x10^{-3}$ Torr, 30 min. G.c./m.s. has indicated the presence of *o*-cresol,

m/z 108; dibenzofuran, *m/z* 168; and 4-methyldibenzofuran *m/z* 182. The ^{1}H n.m.r. spectrum of the pyrolysate has also indicated the presence of xanthene δ_H 4.06 (2H, s, CH_2), and 1-hydroxyfluorene δ_H 3.84 (2H, s, CH_2), which correlate with authentic spectra[140] [δ_H 4.06 (2H, s, CH_2) and δ_H 3.84 (2H, s, CH_2) respectively]. The major product is 4-methyldibenzofuran, which has a calculated yield (see Section B) of 30%; δ_H 8.00-6.91 (7H, m), and 2.61 (3H, s, CH_3).

3-Methylphenyl (2-allyloxy)benzoate

0.077 g (0.28 mmol), 170°C, 650°C, 5×10^{-3} Torr, 30 min. G.c./m.s. indicates the formation of a (1:1) mixture of two isomers; *m/z* 182 (M^+, 100%): 1-methyldibenzofuran and 3-methyldibenzofuran; δ_H 8.09-7.05 (14H, m), 2.81 (3H, s, CH_3), and 2.41 (3H, s, CH_3).

Pyrolysis was repeated on a preparative scale: 0.202 g (0.75 mmol), 180°C, 650°C, 1×10^{-3} Torr, 30 min. After general work-up procedure, the two isomers were obtained unseparated, having a combined yield of 0.11 g (80%).

4-Methylphenyl (2-allyloxy)benzoate

0.821 g (3 mmol), 160°C, 650°C, 1×10^{-3} Torr, 30 min. General work-up procedure afforded *p*-cresol 0.021 g (6%), m.p. 29-30°C (lit.[141] 30-32°C), and 2-methyldibenzofuran 0.38 g (70%), m.p. 37-39°C (from ethanol) (lit.[142] 38-40°C); δ_C 156.35 (q), 154.42 (q), 132.04 (q), 128.09, 126.80,

124.13 (q), 122.56 (q), 122.40, 120.51, 120.42, 111.52, 111.02 and 21.22.

Phenyl (2-allyloxy-4-methyl)benzoate

0.050 g (0.19 mmol), 120°C, 650°C, $1x10^{-3}$ Torr, 30 min. The formation of two isomers is indicated by the ^1H n.m.r. spectrum which shows two methyl signals: δ_H 7.97-7.09 (m), 2.81 (s, CH_3) and 2.53 (s, CH_3), in a ratio of 1:3 respectively.

2-Chlorophenyl (2-allyloxy)benzoate

0.051 g (0.18 mmol), 180°C, 650°C, $1x10^{-3}$ Torr, 30 min. A white crystalline solid and red droplets were obtained. G.c. indicates the presence of one major component and two minor components, one of which is dibenzofuran.

Pyrolysis was repeated on a larger scale: 0.228 g (0.79 mmol), 140°C, 650°C, $1x10^{-3}$ Torr, 90 min. After general work-up, the neutral component was chromatographed on a silica flash column, using ether/hexane as eluant, and 4-chlorodibenzofuran was obtained (0.05 g, 22%); δ_C 156.01 (q), 151.77 (q), 127.66, 126.99, 125.83 (q), 123.87 (q), 123.40, 123.09, 120.81, 118.84, 116.98 (q), and 111.89.

4-Chlorophenyl (2-allyloxy)benzoate

1.625 g (5.6 mmol), 140°C, 650°C, $1x10^{-3}$ Torr, 60 min. Following the general work-up procedure, 2-chloro-

dibenzofuran was isolated (1.21 g, 87%) m.p. 94-96°C (from n-hexane) (lit.[143] 100°C); δ_H 7.97-7.80 (2H, m), and 7.54-7.28 (5H, m).

2,6-Dichlorophenyl (2-allyloxy)benzoate

0.259 g (0.8 mmol), 160°C, 650°C, $1x10^{-3}$ Torr, 90 min. A white crystalline solid and a green oil were obtained. After general work-up a yellow solid was obtained (0.064 g, 39%) which was matched, by g.c., with the pyrolysate of 2-chlorophenyl (2-allyloxy)benzoate, and thus identified as 4-chlorodibenzofuran.

2-Methoxyphenyl (2-allyloxy)benzoate

0.067 g (0.2 mmol), 160°C, 650°C, $1x10^{-3}$ Torr, 40 min. ^{1}H N.m.r. spectroscopy reveals a singlet at δ_H 4.06 which indicates a methoxy group and a singlet at δ_H 9.87, suggesting an aldehyde proton. G.c./m.s. suggests that 4-methoxydibenzofuran is obtained as the major component; *m/z* 198 (M^+, 94%). Minor components present include salicylaldehyde *m/z* 122 (M^+, 3%), and dibenzofuran *m/z* 168 (M^+, 100%).

4-Methoxyphenyl (2-allyloxy)benzoate

0.55 g (2.3 mmol), 170°C, 650°C, $1x10^{-3}$ Torr, 120 min. Work-up afforded 2-methoxydibenzofuran (0.37 g, 80%) m.p. 89-91°C (from ethanol) (lit.[144] 93-94°C); δ_H 7.94-7.89 (1H, m), 7.58-7.25 (5H, m), 7.08-7.02 (1H, m), and 3.91 (3H, s, CH_3); *m/z* 198 (M^+, 100%), 183(60), and 155(49).

4-Nitrophenyl (2-allyloxy)benzoate

0.417 g (1.4 mmol), 150°C, 650°C, $1x10^{-3}$ Torr, 120 min. General work-up afforded 2-nitrodibenzofuran (0.27 g, 90%), m.p. 50-51°C (from ethanol) (lit.[145] 50.5-51.5°C); δ_H 8.84 (1H, m), 8.37 (1H, m), 8.16-7.98 (2H, m), and 7.64-7.38 (3H, m).

4-Cyanophenyl (2-allyloxy)benzoate

0.286 g (1 mmol), 160°C, 650°C, $1x10^{-3}$ Torr, 40 min. Work-up afforded 2-cyanodibenzofuran (0.14 g, 73%), m.p. 132-135°C (from n-hexane) (lit.[146] 140°C); δ_C 157.79 (q), 156.58 (q), 130.66, 128.57, 125.20, 125.08 (q), 123.59, 122.38 (q), 120.91, 119.00 (q), 112.66, 111.91, and 106.42 (q), *m/z* 193 (M^+, 100%).

3. Pyrolysis of Heterocyclic and Polynuclear Aromatic Systems

3-Pyridyl (2-allyloxy)benzoate

0.831 g (4 mmol), 150°C, 650°C, $1x10^{-3}$ Torr, 60 min. Work-up afforded a 3:1 mixture of isomers (0.37 g, 55%), which can be distinguished by ^{13}C n.m.r. (D.E.P.T.) spectroscopy : benzofuro[3,2-*b*]pyridine (major); δ_C 144.99, 129.01, 123.39, 121.06, 120.95, 118.39, and 111.95; benzofuro[2,3-*c*]pyridine (minor); δ_C 142.76, 129.73, 123.22, 121.87, 114.96, 112.25, and 106.28.

The picrate of each isomer was then made as follows:

picric acid (wet with ethanol) (0.6 g, 2.6 mmol) was dissolved in acetone (0.6 ml), and added to the isomeric mixture (0.21 g, 1.2 mmol). The addition of ether (6 ml) completed the crystallisation of the products (0.74 g, 72%). The picrate of the minor isomer was partially purified by recrystallisation (0.26 g, 25%), m.p. 204-207°C (from nitromethane) (lit.[147] 240-241°C). In solution one drop of trifluoroacetic acid was added to maintain the picrate complex; δ_H (d_6-DMSO) 9.63 (1H, s), 8.92-8.81 (2H, m), 8.58 (2H, s), 8.54 (1H, m), 8.04 (1H, m), 7.95 (1H, m), and 7.65 (1H, m).

1-Naphthyl (2-allyloxy)benzoate

0.425 g (1.4 mmol), 150°C, 650°C, 5×10^{-3} Torr, 60 min. G.c. suggests the presence of two isomers and a trace of 1-naphthol. After work-up, the pyrolysate was chromatographed on a silica dry-flash column, however the two isomers were obtained unseparated, with a combined yield of 0.13 g (43%).

2-Naphthyl (2-allyloxy)benzoate

0.052 g (0.17 mmol), 130°C, 650°C, 5×10^{-3} Torr, 60 min. A trace of β-naphthol was detected by g.c., however the ^{13}C n.m.r. (D.E.P.T.) spectrum indicates that two isomers are apparent, one major and one minor: major isomer, δ_C (D.E.P.T.) 129.08, 128.43, 127.02, 125.74, 124.26, 123.33, 123.03, 121.81, 112.58, and 111.75; minor isomer, δ_C (D.E.P.T.) 129.52, 128.20, 127.35, 125.72, 124.15, 122.82, 121.13, 118.97, 111.41, and 106.77.

Pyrolysis was repeated on a preparative scale 0.448 g (1.5 mmol), 130°C, 650°C, $1x10^{-3}$ Torr, 60 min. Work-up afforded both isomers (0.30 g, 91%), and the minor isomer was isolated by recrystallisation to constant melting point, and thus identified as β-brazan (0.061 g, 19%), m.p. 201-202°C (from ethanol/acetic acid) (lit[148] 202°C); δ_C 157.55 (q), 154.76 (q), 132.96 (q), 130.08 (q), 128.22, 127.65, 125.66, 125.33 (q), 124.17, 123.81 (q), 122.63, 121.15, 119.00, 111.44, and 106.80 (two peaks are coincidental at δ_C 128.22).

8-Quinolinoxyl (2-allyloxy)benzoate

0.453 g (1.5 mmol), 150°C, 650°C, $1x10^{-3}$ Torr, 90 min. After general work-up, 8-hydroxyquinoline was obtained as the major product (0.073 g, 34%), m.p. 71-72°C, (from n-hexane/ethyl acetate), mixed m.p. 72°C (lit.[149] 75-76°C); δ_H 8.95-7.15 (6H, m), 5.00 (1H, br, *OH*).

4. Pyrolysis of Allyl (2-propenylthio)benzoate

0.057 g (0.24 mmol), 100°C, 850°C, $1x10^{-3}$ Torr, 30 min. A red oil was obtained, g.c. reveals that one major component is formed, identified as benzothiophene, by correlation with an authentic sample; δ_H 7.85 (1H, m), and 7.53-7.25 (5H, m).

5. Pyrolysis of 2-Allyloxybiphenyl

1.323 g (6.3 mmol), 100°C, 650°C, $1x10^{-3}$ Torr, 60 min. After general work-up procedure, two products were isolated: dibenzofuran (0.69 g, 65%), m.p. 79-81°C (from ethanol) (lit.[134] 82-83°C); δ_H 7.96 (2H, m), and 7.61-7.30 (6H, m), and 2-hydroxybiphenyl (0.18 g, 17%), m.p. 53-55°C (from ethanol) (lit.[150] 56°C); δ_H 7.50 (5H, s), 7.30-7.26 (2H, m), 7.06-6.99 (2H, m), and 5.30 (1H, bs, *OH*).

G Preparation and Pyrolysis of Other Systems Related to Aryl (2-allyloxy)benzoate

1. Aryl (2-allylamino)benzoate and Related Systems

(i) Preparation of N-*Allylisatoic anhydride*

Isatoic anhydride (3.10 g, 0.019 mol) was added to a solution of potassium carbonate (2.63 g, 0.019 mol) in dimethylformamide (50 ml). Allylbromide (2.30 g, 0.019 mol) was added dropwise, and the mixture stirred at room temperature for 21h.

Water (100 ml) was added, and the mixture was extracted with methylene chloride (3x20 ml), because the product is insoluble in ether. The combined organic extracts were then washed with water (2x30 ml), dried ($MgSO_4$), and the solvent removed *in vacuo*. Thus, N-*allylisatoic anhydride* was obtained as a brown solid (3.44 g, 89%) m.p. 104-106°C (from ethanol) (Found: C, 64.8; H, 4.5; N, 6.95. $C_{11}H_9NO_3$ requires C, 65.0; H, 4.45; N, 6.9%); δ_H 8.12 (1H, m), 7.75 (1H, m), 7.31-7.14 (2H, m), 5.89 (1H, m), 5.33-5.21 (2H, m), and 4.71-4.67 (2H, m); δ_C 158.22 (q), 147.55 (q), 141.16 (q), 137.05, 130.54, 129.92, 123.90, 118.43, 114.38, 111.50 (q), and 46.91; *m/z* 203 (M^+, 31%), 159(45), 130(100), and 77(37).

(ii) Preparation of *4-Methylphenyl (2-allylamino)benzoate*

This was adapted from a literature preparation[151]. Thus, finely ground sodium hydroxide (0.004 g, 0.1 mmol) was added to a stirred mixture of *N*-allylisatoic anhydride (0.41 g, 2 mmol) and *p*-cresol (0.22 g, 2 mmol), in 1,4-

dioxan (10 ml). The mixture was then heated on a water bath, and over 30 min the temperature was raised gently to 100°C. After a further 30 min, at this temperature, the reaction mixture was cooled in ice, and the volume was then increased threefold with ice-water.

The solution was then extracted with methylene chloride (2x10 ml), and the combined organic extracts were washed with aqueous sodium hydroxide (2M, 10 ml) then washed with water (15 ml), dried ($MgSO_4$), and the solvent removed *in vacuo*. Thus, *4-methylphenyl (2-allylamino)benzoate* was obtained as a brown oil (0.33 g, 63%) b.p. 150-158°C (0.4 Torr) (Found: M^+ 267.1097. $C_{17}H_{17}NO_2$ requires M^+ 267.1099); δ_H 8.20 (1H, m), 7,52-6.99 (7H, m), 5.98 (1H, m), 5.42-5.07 (2H, m), 3.86 (2H, m), and 2.37 (3H, s); δ_C 167.44 (q), 151.47 (q), 148.44 (q), 135.21 (q), 135.10, 134.12, 131.92, 129.83, 121.56, 116.17, 114.71, 111.54, 108.98 (q), 45.13, and 20.75 *m/z* 267 (M^+, 5%), 159(89), 130(100), and 77(78).

(iii) Pyrolysis of 4-Methylphenyl (2-allylamino)benzoate

0.054 g (0.2 mmol), 150°C, 650°C, $5x10^{-3}$ Torr, 60 min. ^1H n.m.r. spectroscopy and g.c. indicate that *p*-cresol is the major product.

Pyrolysis was repeated at a higher furnace temperature; 0.053 g (0.2 mmol), 150°C, 850°C, $5x10^{-3}$ Torr, 50 min. G.c. and ^1H n.m.r. spectroscopy indicate that *p*-cresol is the major product; δ_H 7.10-6.60 (4H, m), 4.40 (1H, bs, *OH*), and 2.20 (3H, s, CH_3), and that a small quantity of quinoline is also formed; δ_H 8.64 (1H, m), and 8.05-7.00 (6H, m). However, no carbazoles have been detected.

(iv) Pyrolysis of *N*-Allylisatoic anhydride

0.056 g (0.27 mmol), 150°C, 650°C, $1x10^{-3}$ Torr, 45 min. The ^1H n.m.r. spectrum of the entire pyrolysate shows a series of broad signals, which indicate that polymeric-type products have been formed.

Pyrolysis was repeated at a higher furnace temperature, 0.045 g (0.22 mmol), 160°C, 850°C, $1x10^{-3}$ Torr, 30 min. It is apparent from g.c. and ^1H n.m.r. spectroscopy that quinoline is the major product formed at this temperature; δ_H 8.85 (1H, m), and 8.40-6.99 (6H, m).

2. Preparation and Pyrolysis of the (2-Allyloxy)phenyl benzoate System

(i) Preparation of *2-Allyloxyphenol*

Catechol (6.61 g, 0.06 mol) was added to a solution of potassium carbonate (9.95 g, 0.072 mol) in dimethylformamide (60 ml). Allylbromide (8.71 g, 0.072 mol) was then added dropwise and the solution was stirred for sixteen hours.

At this point the reaction mixture should contain mono- and di-allylated catechol. Therefore water (80 ml) was added, and the mixture was washed with aqueous sodium hydroxide (2M, 2x20 ml), to remove the mono-alkylated product. The basic solution was then acidified with aqueous hydrochloric acid (2M, ~20 ml) and extracted with ether (3x15 ml). The combined organic extracts were then

washed with water (20 ml), dried ($MgSO_4$), and the solvent removed *in vacuo*. Thus *(2-allyloxy)phenol* was obtained as a yellow oil (1.81 g, 20%), b.p. 150-155°C (1.5 Torr); δ_H 7.00-6.82 (4H, m), 5.90 (1H, m), 5.52-5.21 (2H, m), and 4.60 (2H, m) (hydroxyl is not apparent); δ_C 145.75 (q), 145.43 (q), 132.76, 121.63, 119.99, 118.16, 114.65, 112.17, and 69.70; *m/z* 150 (M^+, 37%), and 109(66). This compound was used in the following reactions, without further purification.

(ii) Preparation of (2-Allyloxy)phenyl benzoates

These compounds were prepared from the appropriate benzoyl chloride, (2-allyloxy)phenol, and a catalytic amount of 4-dimethylaminopyridine (4-DMAP) by the general procedure described in Section F.1(b)(ii).

The following compounds were thus prepared:

(2-Allyloxy)benzyl benzoate (87%) m.p. 42-44°C (from ethanol) (Found: C, 75.3; H, 5.5. $C_{16}H_{14}O_3$ requires C, 75.6; H, 5.5%); δ_H 8.26-8.22 (2H, m), 7.65-7.60 (1H, m), 7.53-7.48 (2H, m), 7.25-7.17 (2H, m), 7.03-6.98 (2H, m), 5.95 (1H, m), 5.33-5.14 (2H, m), and 4.56 (2H, m); δ_C 164.59 (q), 150.21 (q), 140.35 (q), 133.23, 132.74, 130.10, 129.45 (q), 128.35, 126.63, 122.91, 120.99, 116.94, 114.07, and 69.26; *m/z* 254 (M^+, 18%), 105(100), and 77(23).

(2-Allyloxy)phenyl 4-methylbenzoate (90%) m.p. 40-42°C (from ethanol) (Found: C, 76.1; H, 6.1. $C_{17}H_{16}O_3$ requires C, 76.1; H, 6.0%); δ_H 8.14-8.10 (2H, m); 7.32-7.15 (4H, m), 7.03-6.95 (2H, m), 5.90 (1H, m), 5.35-5.12 (2H, m), 4.54 (2H, m), and 2.44 (3H, s); δ_C 164.61 (q), 150.21 (q),

143.98 (q), 140.37 (q), 132.72, 130.11, 129.05, 126.62 (q), 126.51, 122.93, 120.94, 116.85, 114.01, 69.19, and 21.53; *m/z* 268 (M^+, 28%), 119(100), and 91(92).

(iii) Pyrolysis of (2-Allyloxy)phenyl benzoates

(2-Allyloxy)phenyl benzoate

0.123 g (0.48 mmol), 140°C, 650°C, $5x10^{-3}$ Torr, 60 min. A brown deposit and a dark polymeric material (0.034 g) were obtained. G.c./m.s. revealed that the brown fraction (0.011 g) contained allylbenzene *m/z* 118 (M^+, 84%), 117(100), and 91(33); naphthalene *m/z* 128 (M^+, 100%), biphenyl *m/z* 154 (M^+, 100%), and 77(13), and dibenzofuran *m/z* 168 (M^+, 100%). All of these compounds were further identified by correlation with an authentic sample.

(2-Allyloxy)phenyl 4-methylbenzoate

0.063 g (0.24 mmol), 100°C, 650°C, $5x10^{-3}$ Torr, 90 min. A white crystalline solid and a brown oil were obtained. The entire pyrolysate was analysed by ^1H n.m.r. spectroscopy and g.c./m.s., which indicates that the major product is polymeric, however, a small quantity of 2-methylnaphthalene *m/z* 142 (M^+, 100%) and 2-methyldibenzofuran *m/z* 182 (M^+, 100%) were also detected.

3. Preparation and Pyrolysis of (2-Allyloxy-5-methyl)azobenzene

(i) Preparation of (2-Hydroxy-5-methyl)azobenzene

Aniline (5.0 g, 0.054 mol), was dissolved in concentrated hydrochloric acid (16 ml). Water (16 ml) was added carefully, and the mixture was immersed in an ice bath, with stirring, until the temperature stabilised below 5°C. A solution of sodium nitrite (4.0 g, 0.058 mol) in water (20 ml) was chilled and added in small volumes (2-3 ml), to the cold aniline hydrochloride solution. The temperature was maintained below 10°C to prevent decomposition of the diazonium salt and of the nitrous acid.

A solution of *p*-cresol (5.84 g, 0.054 mol) in aqueous sodium hydroxide (10%, 40 ml) was stirred vigorously, chilled and added slowly to the cold diazonium salt solution. The product was filtered under suction, and obtained as a brown solid (9.12 g, 80%); m.p. 104-107°C (from glacial acetic acid) (lit [152] 108-109°C); δ_H 9.60 (1H, bs, *OH*), 7.92-6.87 (8H, m), and 2.38 (3H, s, CH_3); *m/z* 212 (M^+, 96%), 135(42), and 107(100).

(ii) Preparation of *(2-Allyloxy-5-methyl)azobenzene*

(2-Hydroxy-5-methyl)azobenzene (2.0 g, 0.0094 mol) was added to a solution of potassium carbonate (2.60 g, 0.019 mol), in dimethylformamide (25 ml). Allyl bromide (2.27 g, 0.019 mol) was added dropwise and the mixture

was stirred at room temperature for 21h.

Water (30 ml) was added and the mixture was extracted with ether (3x10 ml). The combined organic extracts were washed with water (20 ml), dried ($MgSO_4$), and the solvent removed *in vacuo*. *2-Allyloxy-5-methylazobenzene* was obtained as a red solid (2.20 g, 97%), m.p. 42-44°C (from methanol) (Found: C, 76.3; H, 6.45; N, 11.2. $C_{16}H_{16}N_2O$ requires C, 76.2; H, 6.35; N, 11.1%); δ_H 8.03-6.97 (8H, m), 6.15 (1H, m), 5.55-5.27 (2H, m), 4.75 (2H, m), and 2.34 (3H, m, CH_3); δ_C 154.20 (q), 153.10 (q), 142.53 (q), 133.28, 132.65, 130.64, 128.84, 123.01, 122.81, 119.65 (q), 117.15, 115.47, 70.81, and 20.34; *m/z* 252 (M^+, 3%), 160(26), 131(24), 77(75), and 41(100).

(iii) Pyrolysis of (2-Allyl-5-methyl)azobenzene

0.185 g (7.3 mmol), 160°C, 650°C, $5x10^{-3}$ Torr, 75 min: Due to low volatility of the azobenzene a black residue was formed in the inlet (0.025 g). Yellow droplets and a red polymeric-type material were deposited in the cold trap (0.16 g); δ_H 7.88-6.66 (m), 3.25 (s), 2.78 (s), 2.60 (s), 2.50 (s), and 2.43 (s). This material was distilled, producing a clear oil (0.07 g), b.p. 148-152°C (1.2 Torr).

T.l.c. suggested that 2-methyldibenzofuran may be formed, as well as several other impurities. Therefore the mixture was chromatographed on a silica flash column, using n-hexane/ether as eluant. The major component

was isolated as a yellow solid (0.036 g, 28%). G.c./m.s. revealed that this component had *m/z* 182 (M^+, 100%), 152(25), and 40(71), consistent with authentic 2-methyldibenzofuran. The other mixed fractions were analysed by g.c./m.s. but no significant products were detected.

Pyrolysis was repeated at furnace temperatures of 750°C and 850°C, but ^{1}H n.m.r. spectroscopy and gas chromatography indicated no change in product formation.

H Preparation and Pyrolysis of (2-Allyloxybenzylidine)-aniline and Benzylidine-(2-allyloxyaniline)

1. Preparation of (2-Allyloxy)benzaldehyde

Benzaldehyde (20.76 g, 0.17 mol) was added to a solution of potassium carbonate (46.99 g, 0.34 mol) in dimethylformamide (250 ml). Allyl bromide (41.13 g, 0.34 mol) was added dropwise, and the mixture stirred for 21h.

Water (300 ml) was then added and the mixture extracted with ether (3x50 ml). The combined organic extracts were washed with water (100 ml), dried ($MgSO_4$), and the solvent removed *in vacuo*, to give *(2-allyloxy)benzaldehyde* as a colourless viscous liquid (23.26 g, 84%), b.p. 115-118°C (0.4 Torr) (Found: M^+ 162.0678; $C_{10}H_{10}O_2$ requires M^+ 162.0680); δ_H 10.40 (1H, s, C*H*O), 7.72 (1H, m), 7.40 (1H, m), 6.93-6.84 (2H, m), 5.97 (1H, m), 5.39-5.18 (2H, m), and 4.52 (2H, m); δ_C 189.37, 160.68 (q), 135.63, 132.17, 128.06, 124.80, 120.56, 117.72, 112.67, and 68.87. *m/z* 162 (M^+, 56%), 133(32), 121(90), 92(37), and 41(100).

2. Preparation of (2-Allyloxybenzylidine)aniline

2-Allyloxybenzaldehyde (2.43 g, 0.015 mol) was added to aniline (1.40 g, 0.015 mol) in ethanol (8 ml), and the mixture was stirred at room temperature for 10 min. The solvent was then removed *in vacuo* to give *(2-allyloxybenzylidine)aniline*, as a yellow oil (1.61 g, 45%), b.p. 166-170°C (0.4 Torr), (Found: C, 80.8; H, 6.4; N, 5.95.

$C_{16}H_{15}NO$ requires C, 81.0; H, 6.35; N, 5.9%); δ_H 9.00 (1H, s), 8.20 (1H, m), 7.47-6.93 (8H, m), 6.08 (1H, m), 5.50-5.28 (2H, m), and 4.63 (2H, m); δ_C 158.53 (q), 156.10, 152.77 (q), 132.86, 132.32, 128.87, 127.60, 125.44, 120.99, 120.86, 117.49, 114.93 (q), 112.53, and 69.21; *m/z* 237 (M^+, 19%), 121(90), 93(100), 77(52), and 41(95).

3. Preparation of Benzylidine-(2-allyloxyaniline)

(i) *N*-Acetyl-2-hydroxyaniline

This was prepared by the method described in Vogel[153] thus acetic anhydride (10.72 g, 0.105 mol), glacial acetic acid (10.51 g, 0.175 mol), 2-hydroxyaniline (12.0 g, 0.11 mol) and zinc dust (0.05 g), were heated together, under reflux, for thirty minutes.

The hot solution was then poured into ice-water (250 ml), stirred continuously, and chilled in an ice-bath. The resulting precipitate was filtered, and washed with water (2x30 ml). The product was obtained as a pink solid (11.59 g, 70%) m.p. 207-209°C (from water) (lit[154] 208-210°C).

(ii) *N*-Acetyl-2-Allyloxyaniline

N-Acetyl 2-hydroxyaniline (7.55 g, 0.05 mol) was added to potassium carbonate (6.91 g, 0.05 mol) in dimethyl-formamide (50 ml). Allylbromide (6.05 g, 0.05 mol) was then added dropwise, and the mixture was stirred for 21h.

After the general work-up procedure described in Section D.2, *N*-acetyl-2-allyloxyaniline was obtained as a brown solid (5.49 g, 58%), m.p. 48-50°C (from n-hexane) (lit.[155] 50-51°C); δ_H 8.30 (1H, m), 7.80 (1H, bs, *NH*), 7.02-6.80 (3H, m), 6.01 (1H, m), 5.50-5.20 (2H, m), 4.59 (2H, m), and 2.15 (3H, s, *CH*$_3$); δ_C 167.86 (q), 146.57 (q), 132.66, 127.80 (q), 123.31, 121.04, 119.81, 117.87, 111.26, 69.30, and 24.58.

(iv) 2-Allyloxyaniline

Preparation was achieved using the method reported by Tiffany[155]. *N*-Acetyl-2-allyloxyaniline (3.5 g, 0.018 mol) and aqueous hydrochloric acid (6M, 20 ml) were heated together, under reflux for one hour. The mixture was basified by the addition of 20% aqueous sodium hydroxide, and the resulting solution was then extracted with ether (2x20 ml). The combined organic extracts were washed with water (50 ml), dried ($MgSO_4$), and the solvent removed under vacuum. 2-Allyloxyaniline was obtained as a red oil (1.51 g, 56%) and was used without purification, in the next stage.

(v) Benzylidine-(2-allyloxyaniline)

Benzaldehyde (0.99 g, 9.4 mmol) was added to 2-allyloxyaniline (1.40 g, 9.4 mmol) in ethanol (15 ml), and the mixture was stirred for thirty minutes. The solvent was then removed under vacuum, affording the product as a red oil (1.88 g, 85%) b.p. 170-180°C (0.4 Torr) (Found: M^+ 237.1094; $C_{16}H_{15}NO$ requires M^+ 237.1098); δ_H 8.55 (1H, s),

8.10-7.80 (2H, m), 7.65-7.30 (3H, m), 7.12-6.75 (3H, m), 6.22 (1H, m), 5.60-5.12 (2H, m), and 4.63 (2H, m); *m/z* 237 (M^+, 64%), 196(89), 160(11), and 40(100).

4. Pyrolysis of (2-Allyloxybenzylidine)aniline

1.50 g (6.3 mmol), 120°C, 650°C, $1x10^{-3}$ Torr, 120 min. A yellow solid (0.81 g) and a pale coloured oil (0.28 g) were obtained. Analysis of the liquid fraction by g.c. and by comparison with an authentic sample, revealed the presence of a trace of biphenyl. Recrystallisation of the solid deposit afforded pure *o*-cyanophenol, (0.29 g, 39%), identified by melting point correlation, m.p. 91-93°C (from ethanol) (lit.[156] 92-94°C); δ_H 7.53-7.26 (2H, m), 7.19-6.80 (2H, m), and 6.18 (1H, bs, *OH*); *m/z* 119 (M^+, 100%), 91(87), 64(30), and 38(14).

5. Pyrolysis of Benzylidine-(2-allyloxyaniline)

0.052 g (0.22 mmol), 120°C, 650°C, $1x10^{-3}$ Torr, 30 min. A black oil (0.031 g) was obtained. The ^1H n.m.r. spectrum of the entire pyrolysate showed signals in the aromatic region only, and analysis by g.c. and g.c./m.s. revealed the presence of 2-phenylbenzoxazole *m/z* 195 (also matched with an authentic sample) as the major product, together with traces of benzonitrile *m/z* 103 and benzoxazole *m/z* 119.

I Preparation and Pyrolysis of (2-Allyloxy)stilbene and Related Compounds

1. Preparation of (2-Allyloxy)stilbene

This was adapted from the literature method described by Wheeler and Batlle de Pabon[157]. Thus benzyltriphenylphosphonium bromide (6.94 g, 0.016 mol) was added to a solution of sodium ethoxide [from sodium (0.46 g, 0.02 mol)] in 'super-dry' ethanol (50 ml), under nitrogen, forming an orange suspension. (2-Allyloxy)benzaldehyde (2.58 g, 0.016 mol) in dry ethanol (10 ml), was then added dropwise, thus forming a clear solution. The mixture was stirred at room temperature for 50h.

The solution was then poured into 33% hydrobromic acid in acetic acid (50 ml), and cooled in an ice-bath. The resulting pink precipitate of recovered phosphonium salt was filtered (2.22 g, 5.12 mmol). The filtrate was extracted with ether (3x30 ml), and the combined organic extracts were washed with 5% sodium bisulphite solution (40 ml). The ether extract was filtered and triphenylphosphine oxide was deposited as a white solid (1.57 g, 35%). The filtrate was evaporated to dryness, and a viscous brown oil was obtained (3.42 g). Distillation yielded *(2-allyloxy)-stilbene* as a clear oil (1.40 g, 37%) b.p. 184-187°C (0.6 Torr), which slowly crystallised, m.p. 46-48°C (from ethanol) (Found: C, 85.5; H, 6.8. $C_{17}H_{16}O.0.1H_2O$ requires C, 85.8; H, 6.8%); δ_H 7.80-6.87 (11H, m), 6.15 (1H, m), 5.56-5.28 (2H, m), and 4.66 (2H, m); δ_C 155.87 (q), 137.89 (q),

133.31, 129.02, 128.51, 128.46, 127.27, 126.71 (q), 126.46, 126.42, 123.47, 120.91, 117.19, 112.45, and 69.13; *m/z* 236 (M^+, 33%), 195(26), 167(100), 152(57), and 41(63).

2. Preparation of Dimethyl (2-Allyloxy)phenylmethylene malonate

A solution of titanium tetrachloride (2.2 ml, 0.02 mol) in carbontetrachloride (5 ml) was added dropwise to ice-cold anhydrous T.H.F. (40 ml), under an atmosphere of nitrogen. Dimethylmalonate (1.32 g, 0.01 mol) and 2-allyloxybenzaldehyde (1.62 g, 0.01 mol) in anhydrous T.H.F. (10 ml) were then added slowly, followed by the addition of pyridine (3.2 ml, 0.04 mol) in dry T.H.F. (5 ml). The resulting thick red suspension was then stirred at 0°C for 1h.

Water (50 ml) was added and the mixture extracted with methylene chloride (2x25 ml). The combined organic extracts were washed, firstly with brine (20 ml), then with saturated sodium bicarbonate solution (20 ml), and finally with water (30 ml). The combined extracts were then dried ($MgSO_4$) and the solvent was removed under vacuum. Thus, *(2-Allyloxyphenyl)methylenedimethylmalonate* was obtained as a yellow oil (1.69 g, 61%), b.p. 187-190°C (1.0 Torr), (Found: C, 64.9; H, 5.9. $C_{15}H_{16}O_5$ requires C, 65.2; H, 5.8%), δ_H 8.14 (1H, s, *CH*), 7.29 (2H, m), 6.87 (2H, m), 6.01 (1H, m), 5.41-5.22 (2H, m), 4.54 (2H, m), 3.80 (3H, s, OCH_3), and 3.74 (3H, s, OCH_3); δ_C 166.98 (q), 164.52 (q),

156.96 (q), 138.73, 132.56, 131.86, 128.74, 125.22 (q), 122.34 (q), 120.57, 117.48, 112.18, 69.04, 52.27, and 52.19; *m/z* 276 (M^+, 35%), 217(12), 173(100), 145(50), and 117(45).

3. Preparation of (2-Allyloxyphenyl)methylenemalononitrile and Methyl (2-allyloxyphenyl)methylenecyanoacetate

Malononitrile (0.198 g, 3 mmol) and (2-allyloxy)-benzaldehyde (0.49 g, 3 mmol) were added together in toluene (15 ml). Five drops each of piperidine and acetic acid were then added and the mixture was stirred at room temperature for 21h. Water (20 ml) was then added, followed by extraction with methylene chloride (2x10 ml). The combined organic extracts were dried ($MgSO_4$) and the solvent removed *in vacuo*. Thus,

(2-allyloxyphenyl)methylenemalononitrile was obtained as a brown oil which slowly crystallised (0.52 g, 83%), m.p. 50-52°C (from ethanol) (Found: C, 74.2; H, 4.8; N, 13.3. $C_{13}H_{10}N_2O$ requires C, 74.3; H, 4.75; N, 13.3%); δ_H 8.30 (1H, s), 8.16 (1H, m), 7.55 (1H, m), 7.08-6.94 (2H, m), 6.02 (1H, m), 5.46-5.32 (2H, m), and 4.63 (2H, m); δ_C 157.87 (q), 154.31, 136.33, 131.75, 128.65, 121.17, 120.19 (q), 118.76, 114.23 (q), 112.90 (q), 112.64, 81.16 (q), and 69.54; *m/z* 210 (M^+, 35%), 183(91), 143(20), 41(100), and 39(70).

Methyl (2-allyloxyphenyl)methylenecyanoacetate was prepared similarly from methyl cyanoacetate (0.30 g, 3 mmol) and 2-allyloxybenzaldehyde (0.49 g, 3 mmol). The product was obtained as a yellow solid (0.71 g, 97%), m.p. 63-65°C

(from ethanol) (Found: C, 67.6; H, 5.2; N, 5.4. $C_{14}H_{13}NO_3.0.3H_2O$ requires C, 67.6; H, 5.5; N, 5.6%); δ_H 8.81 (1H, s), 8.29 (1H, m), 7.48 (1H, m), 7.09-6.90 (2H, m), 6.01 (1H, m), 5.45-5.28 (2H, m), 4.64 (2H, m), and 3.91 (3H, s, OCH_3); δ_C 163.13 (q), 158.12 (q), 149.88, 134.77, 132.10, 129.23, 120.96, 120.75 (q), 118.00, 115.68 (q), 112.30, 101.83 (q), 69.21, and 53.03; *m/z* 243 (M^+, 29%), 201(15), 182(51), 143(34), and 41(100).

4. Preparation of Methyl (2-Allyloxyphenyl)methylene-propionate

Methylpropionatetriphenylphosphonium bromide was prepared by the method described by Isler *et al.*[158]. Thus, triphenylphosphine (16.79 g, 0.064 mol) and methyl DL-2-bromopropionate (10.02 g, 0.06 mol) were added together in benzene (80 ml) and stirred at room temperature for thirty minutes. The mixture was heated to reflux in a water bath for 4h. The product was deposited as a white solid (6.82 g, 27%).

The ylid was obtained by dissolving the phosphonium salt in water (40 ml), followed by the dropwise addition of aqueous sodium hydroxide (2M, 30 ml), producing a yellow gum which crystallised after trituration in n-hexane, m.p. 151-153°C (from n-hexane/ethyl acetate) (lit.[159] 152-153°C).

The Wittig reaction was carried out by the method described by House and Rasmusson[159]. Thus, 2-allyloxy-

benzaldehyde (0.3 g, 1.7 mmol) in methylene chloride (5 ml) was added dropwise to a solution of the ylid (0.49 g, 1.4 mmol) in methylene chloride (25 ml). The solution was heated to reflux for 3.5h. After cooling, the mixture was concentrated to half its volume and light petroleum (b.p. 40-60°C) (20 ml) added until a dense white precipitate of triphenylphosphine oxide was formed, and this was removed by filtration. The filtrate was concentrated to a brown oil (0.42 g) which contained a mixture of product and starting material.

Attempts to remove (2-allyloxy)benzaldehyde by flash column chromatography proved unsuccessful. Therefore, the aldehyde was removed as a water-soluble hydrazone using Girards "T" reagent (trimethylaminoacetohydrazide chloride)

The mixture (0.29 g) containing approximately (0.1 g, 0.62 mmol) of aldehyde was dissolved in ethanol (20 ml), and the solution acidified with acetic acid (approximately 10 ml). Girard's reagent "T" (0.12 g, 0.72 mmol) was added and the reaction mixture was stirred and heated to just under reflux for 1h.

After cooling, the mixture was added to water (20 ml) and exhaustively extracted with ether (3x10 ml). The combined organic extracts were washed with aqueous sodium carbonate solution (20 ml), dried ($MgSO_4$), and the solvent removed *in vacuo*. The pure product was obtained as a clear oil (0.16 g, 50%) b.p. 162-166°C (1.5 Torr) (Found: M^+ 232.1097; $C_{14}H_{16}O_3$ requires M^+ 232.1099); δ_H 7.87 (1H, s), 7.31-7.23 (2H, m), 6.99-6.87 (2H, m), 6.00 (1H, m),

5.45-5.24 (2H, m), 4.57 (2H, m), 3.80 (3H, s, OCH_3), and 2.05 (3H, s, CH_3); δ_C 168.97 (q), 156.43 (q), 134.82, 132.96, 130.07, 129.49, 128.11 (q), 125.05 (q), 120.13, 117.17, 111.86, 68.87, 51.76, and 14.10 (appears to be only one geometrical isomer); *m/z* 232 (M^+, 49%), 131(76), and 41(100).

5. Pyrolysis of (2-Allyloxy)stilbene and Related Compounds

(2-Allyloxy)stilbene

0.053 g (0.225 mmol), 110°C, 650°C, $1x10^{-3}$ Torr, 30 min. A white crystalline deposit was obtained. ^1H n.m.r. spectroscopy revealed signals in the aromatic region only. From g.c. three peaks were apparent, by matching with authentic samples, the two minor peaks were identified as benzofuran and biphenyl.

Pyrolysis was repeated on a larger scale: 0.387 g (1.6 mmol), 110°C, 650°C, $1x10^{-3}$ Torr, 90 min. The entire pyrolysate was washed from the trap with methylene chloride (15 ml), and the solvent removed *in vacuo*, producing a white solid (0.21 g). Recrystallisation from ethanol to constant melting point afforded 2-phenylbenzofuran (0.17 g, 55%), m.p. 113-115°C (lit.[160] 121°C) as the major product; *m/z* 194 (M^+, 100%), 165(47), and 77(11).

Dimethyl (2-Allyloxyphenyl)methylenemalonate

0.335 g (1.2 mmol), 130°C, 650°C, $1x10^{-3}$ Torr, 90 min. The crystalline deposit obtained was washed out of the trap

with methylene chloride (15 ml), and the solvent removed *in vacuo*. The resulting solid was identified as methyl benzofuran-2-carboxylate (0.20 g, 95%) m.p. 51-52°C (from n-hexane) (lit.[161] 54-55°C); δ_H 7.68-7.24 (5H, m), and 3.95 (3H, s, OCH_3), *m/z* 176 (M^+, 78%), 145(100), and 117(8). No other products were detected.

(2-Allyloxyphenyl)methylenemalononitrile

0.035 g (0.16 mmol), 110°C, 650°C, $5x10^{-3}$ Torr, 30 min. A yellow solid and some polymeric material were obtained. The solid was scraped from the trap (0.011 g, 31%) and mass spectroscopy showed a base peak at *m/z* 168 (M^+, 100%) and a major fragmentation peak at *m/z* 143. However, no suitable structure could be rationalised from this information.

Methyl (2-allyloxyphenyl)methylenecyanoacetate

0.134 g (0.55 mmol), 150°C, 650°C, $1x10^{-3}$ Torr, 90 min. An inlet residue (0.029 g) was obtained and a white crystalline solid was deposited in the trap. The entire pyrolysate was washed from the trap with chloroform (15 ml), and chromatographed on a silica flash column, using n-hexane/ether as eluant to remove some oligomeric impurities. From ^1H n.m.r. spectroscopy, g.c. and g.c./m.s. the major product was identified as 2-cyanobenzofuran (0.041 g, 52%), δ_H 7.67 (1H, m), and 7.58-7.31 (4H, m); *m/z* 143 (M^+, 100%).

Methyl (2-allyloxyphenyl)methylenepropionate

0.036 g (0.16 mmol), 100°C, 650°C, 1×10^{-3} Torr, 45 min. Yellow droplets were obtained and the entire pyrolysate was dissolved in deuterated chloroform (5 ml). G.c. and g.c./m.s. revealed that one major product and some minor volatiles had been formed. The major product was identified as 2-methylbenzofuran; *m/z* 132 (M^+, 100%); δ_H 7.48-7.37 (2H, m), 7.25-7.14 (2H, m), 6.36 (1H, m), and 2.44 (3H, s, CH_3).

REFERENCES

References

1. D.P. Curren, Synthesis, 1988, 417.
2. B. Giese, 'Radicals in Organic Chemistry: Formation of Carbon-Carbon Bonds,' Pergamon Press, Oxford, 1986.
3. A.L.J. Beckwith, C.J. Easton, and A.K. Serelis, J.Chem.Soc.,Chem.Commun., 1980, 483.
4. M. Ramaiah, Tetrahedron, 1987, 43,
5. D. Hart, Science, 1984, 223, 883.
6. C. Walling, Tetrahedron, 1985, 41, 3887.
7. H. Fischer and H. Paul, Acc.Chem.Res., 1987, 20, 200.
8. H.G. Kuivila, Acc.Chem.Res., 1968, 1, 299.
9. M.D. Johnson, Acc.Chem.Res., 1983, 16, 343.
10. D.H.R. Barton, D. Crich, and W.B. Motherwell, Tetrahedron, 1985, 41, 3901.
11. D.H.R. Barton, D. Crich, and P. Potier, Tetrahedron Lett., 1985, 26, 5943.
12. D.H.R. Barton, D. Crich, Y. Hervé, P. Potier, and J. Thierry, Tetrahedron, 1985, 41, 4347.
13. C. Walling and E.S. Huyser, Org.React., 1963, 13, 91.
14. V.F. Patel, G. Pattenden, and J.J. Russell, Tetrahedron Lett., 1986, 27, 2303.
15. R. Pschorr, Ber.Deut.Chem.Ges., 1896, 29, 496.
16. D.F. Detar, Org.React., 1957, 9, 409.
17. R.A. Abramovitch, Can.J.Chem., 1960, 38, 2273.

18. B. Chauncy and E. Gellert, Aust.J.Chem., 1969, 22, 993.

19. J.I.G. Cadogan, 'Free Radicals in Solution', Butterworths, London, 1966, p.153; and J.I.G. Cadogan, 'Principles of Free Radical Chemistry', The Chemical Society, London, 1973.

20. D.H.Hey and P. Mulley, J.Chem.Soc., 1952, 2276.

21. Reference 16, p.417.

22. A. Effio, D. Griller, K.U. Ingold, A.L.J. Beckwith, and A. Serelis, J.Am.Chem.Soc., 1980, 102, 1734.

23. A.L.J. Beckwith and G. Moad, J.Chem.Soc.,Chem. Commun., 1974, 472.

24. R.D. Rieke and N.A. Moore, J.Org.Chem., 1972, 37, 413.

25. M.E. Keuhne and D.A. Horne, J.Org.Chem., 1975, 40, 1278.

26. B.P. Roberts and J.N. Winter, J.Chem.Soc.,Perkin Trans.2, 1979, 1353.

27. J.C. Cottard and M. Julia, Terrahedron, 1972, 28, 5615.

28. A.L.J. Beckwith and C.H. Schiesser, Tetrahedron, 1985, 41, 3925.

29. T.J. Barton and A. Revis, J.Am.Chem.Soc., 1984, 106, 3802.

30. D.A. Burnett, J.K. Choi, D.J. Hart, Y.M. Tsai, J.Am.Chem.Soc., 1984, 106, 8201.

31. M.A.M. Bradney, A.D. Forbes, and J. Wood, J.Chem. Soc.,Perkin Trans.2, 1973, 1655.

32. G. Stork and R. Mook, Jr., Tetrahedron Lett., 1986, 27, 4529.

33. M. Newcomb and T.M. Deeb, J.Am.Chem.Soc., 1987, 109, 3163.

34. A. Padwa, H. Nimmesgern, and G.S.K. Wong, J.Org. Chem., 1985, 50, 5620.

35. Y. Ueno, O. Moriya, K. Chino, M. Watanabe, and M. Okawara, J.Chem.Soc.,Perkin Trans.1, 1986, 1351.

36. G. Stork, R. Mook, Jr., S.A. Biller, and S.D. Rynchovsky, J.Am.Chem.Soc., 1983, 105, 3741.

37. M. Ladlow and G. Pattenden, Tetrahedron Lett., 1984, 25, 4317.

38. K. Shankaran, C.P. Sloan, and V. Sniekus, Tetrahedron Lett., 1985, 26, 6001.

39. J.K. Choi and D.J. Hart, Tetrahedron, 1985, 41, 3959.

40. J. Knight, P.J. Parsons, and R. Southgate, J.Chem. Soc.,Chem.Commun., 1986, 78.

41. G. Stork and N.H. Baine, J.Am.Chem.Soc., 1982, 104, 2321.

42. D. Crich, K.A. Eustace, and T.J. Ritchie, Heterocycles, 1989, 28, 67.

43. J.W. Wilt, Tetrahedron, 1985, 41, 3979.

44. D.F. Detar and S.V. Sagmanti, J.Am.Chem.Soc., 1950, 72, 965.

45. N.M. Cullinane, A.G. Rees, and C.A.J. Plummer, J.Chem.Soc., 1939, 151.

46. R.A. Heacock and D.H. Hey, J.Chem.Soc., 1952, 4059.

47. P.J. Bunyan and D.H. Hey, Proc.Chem.Soc., 1959, 366.

48. J. Russell and R.H. Thomson, J.Chem.Soc., 1962, 3379.

49. M. Tiecco, J.Chem.Soc.,Chem.Commun., 1965, 555.

50. G.M. Badger and C.P. Whittle, Aust.J.Chem., 1963, 16, 440.

51. A.J. Neale, T.J. Rawlings, and E.B. McCall, Tetrahedron, 1965, 21, 2877.

52. J. Grimshaw, R. Hamilton, and J.-T. Grimshaw, J.Chem.Soc.,Perkin Trans.1, 1982, 229.

53. J.K. Kochi and R.D. Gilliam, J.Am.Chem.Soc., 1964, 86, 5251.

54. J.R. Lewis, J.Chem.Soc., 1962, 2533.

55. R.M. Thomson and A.G. Wylie, J.Chem.Soc., 1966, 321.

56. D.B. Denney and P.P. Klemchuk, J.Am.Chem.Soc., 1958, 80, 3289.

57. J.W. Wilt, 'Free Radicals', Vol.1, ed. J.K. Kochi, Wiley-Interscience, New York, 1973, p.346.

58. R.A. Abramovitch, 'Advances in Free Radical Chemistry', Vol.2, ed. G.H. Williams, Academic Press, New York, 1967, p.87.

59. I.C. Lewis and L.S. Singer, Carbon (Oxford), 1967, 5, 373.

60. e.g. J.P. Schirmann and J.M. Weiss, Tetrahedron Lett., 1967, 5163.

61. R.F.C. Brown, 'Pyrolytic Methods in Organic Chemistry' Academic Press, New York, 1980; and references therein.

62. C.H. Depuy and R.W. King, Chem.Rev., 1960, 60, 431.

63. A.E. Ardis, S.J. Averill, H. Gilbert, F.F. Miller, R.F. Schmidt, F.D. Stewart, and H.L. Trumbull, J.Am.Chem.Soc., 1950, 72, 3127.

64. C. Wentrup, Top.Curr.Chem., 1976, 62, 173.

65. J.I.G. Cadogan, C.L. Hickson, and H. McNab, Tetrahedron, 1986, 42, 2135.

66. E.C. Leonard, Jr., J.Org.Chem., 1962, 27, 1921.

67. W.S. Trahanovsky, C.C. Ong, and J.A. Lawson, J.Am.Chem.Soc., 1968, 90, 2839.

68. H. Higuchi, T. Otsubo, F. Ogura, H. Yamaguchi, Y. Sakata, and S. Misumi, Bull.Chem.Soc.Jpn., 1982, 55, 182.

69. F.A. Davis, T.W. Panunto, S.B. Awad, R.L. Billmers, and T.G. Squires, J.Org.Chem., 1984, 49, 1228.

70. E.K. Fields and S. Meyerson, Acc.Chem.Res., 1969, 2, 273.

71. R.A. Marty and P. de Mayo, J.Chem.Soc.,Chem.Commun., 1971, 127.

72. J.I.G. Cadogan, C.L. Hickson, and H. McNab, J.Chem.Res., 1983, (S) 243; (M) 2247.

73. K.J. Bird, A.W.K. Chan, and W.D. Crow, Aust.J.Chem., 1976, 29, 2281.

74. C.L. Hickson and H. McNab, J.Chem.Soc.,Perkin Trans.1, 1984, 1569.

75. H. McNab, J.Chem.Soc.,Chem.Commun., 1980, 442.

76. A.C. Barefoot and F.A. Carroll, J.Chem.Soc.,Chem. Commun., 1974, 357.

77. A.G. Harrison, L.R. Hannen, H.J. Dauben, Jr., and F.P. Lossing, J.Am.Chem.Soc., 1960, 82, 5594.

78. W.D. Crow and H. McNab, Aust.J.Chem., 1979, 32, 111.

79. I.P. Fisher, T.F. Palmer, and F.P. Lossing, J.Am. Chem.Soc., 1964, 86, 2741.

80. F.A. Davis, S.B. Awad, R.H. Jenkins, Jr., R.A. Billmers, and L.A. Jenkins, J.Org.Chem., 1983, 48, 3071.

81. J.I.G. Cadogan, J.B. Husband, and H. McNab, J.Chem.Soc.,Perkin Trans.2, 1983, 697.

82. H. McNab and G.S. Smith, J.Chem.Soc.,Perkin Trans.1, 1984, 381.

83. J.I.G. Cadogan, H.S. Hutchison, and H. McNab, J.Chem.Soc.,Perkin Trans.1, 1987, 1407.

84. J.I.G. Cadogan, C.L. Hickson, H.S. Hutchison, and H. McNab, J.Chem.Soc.,Perkin Trans.1, (submitted).

85. W. Ando, T. Oikawa, K. Kishi, T. Saiki, and T. Migita, J.Chem.Soc.,Chem.Commun., 1975, 704.

86. L.H. Klemm and J.N. Louris, J.Heterocycl.Chem., 1984, 21, 785.

87. H.S. Hutchison, Ph.D.Thesis, University of Edinburgh, 1987.

88. A. Ohsawa, T. Kawaguchi, and H. Igeta, Synthesis, 1983, 1037.

89. J.I.G. Cadogan, C.L. Hickson, H.S. Hutchison, and H. McNab, J.Chem.Soc.,Chem.Commun., 1985, 643.

90. C.L. Hickson and H. McNab, Synthesis, 1981, 464.

91. H. McNab, J.Chem.Soc.,Perkin Trans.1, 1984, 371.

92. H. McNab, J.Chem.Soc.,Perkin Trans.1, 1982, 1941.

93. S. Murahashi and S. Horie, Chem.Abstr.,1959, 54, 24786a.

94. J.I.G. Cadogan, C.L. Hickson, J.B. Husband, and H. McNab, J.Chem.Soc.,Perkin Trans.1, 1985, 1891.

95. J.F. Grove, Biochem.J., 1952, 50, 648.

96. M.V. Sargent and P.O. Stransky, Adv.Heterocycl. Chem., 1984, 35, 2.

97. J. Blair, J.J. Brown, and G.T. Newbold, J.Chem. Soc., 1955, 708.

98. W.J. Bailey and C.N. Bird, J.Org.Chem., 1958, 23, 996.

99. B.T. Tozer and S. Smiles, J.Chem.Soc., 1938, 1897; and Burnett and Zahler, Chem.Rev., 1951, 49, 273.

100. G. Höfle and W. Steglich, Synthesis, 1972, 619.

101. D.S. Tarbell and M.A. McCall, J.Am.Chem.Soc., 1952, 74, 48.

102. J.I.G. Cadogan, C.L. Hickson, and H. McNab, J.Chem. Soc.,Perkin Trans.1, 1985, 1885.

103. N.M. Cullinane, J.Chem.Soc., 1930, 2268.

104. K.-P. Zeller and S. Berger, J.Chem.Soc.,Perkin Trans.2, 1977, 54.

105. F.M. Dean, A.M. Osman, and A. Robertson, J.Chem.Soc., 1955, 11.

106. K. Schimmelschmidt, Liebigs Ann.Chem., 1950, 566, 184.

107. H. Gilman and A.L. Jacoby, J.Org.Chem., 1938, 3, 108.

108. e.g. R.B. Miller and S. Ongar, Organometallics, 1984, 3, 1261.

109a T.J. Batterham, 'N.M.R. Spectra of Simple Heterocycles', Wiley, New York, 1973.

109b J.A. Joule and G.F. Smith, 'Heterocyclic Chemistry', Van Nostrand Reinhold, London, 1978, p.58.

110. T.S. Osdene and P.B. Russell, J.Org.Chem., 1966, 31, 2646.

111. S.C. Dickerman and G.B. Vermont, J.Am.Chem.Soc., 1962, 84, 4150.

112. G.E. Hardtmann, G. Koletar, and O.R. Pfister, J.Heterocycl.Chem., 1975, 12, 565.

113. Y. Mao and V. Boekelheide, J.Org.Chem., 1980, 45, 1547.

114. L.H. Klemm, J. Shabtai, D.R. McCoy, and W.K.T. Kiang, J.Heterocycl.Chem., 1968, 5, 883.

115. H. McNab and M.E.-A. Murray, J.Chem.Soc.,Perkin Trans.1, 1989, 583.

116. E.K. Fields and S. Meyerson, J.Am.Chem.Soc., 1967, 89, 724.

117. D.C. Dejongh and D.A. Brent, J.Org.Chem., 1970, 35, 4204.

118. C.L. Hickson and H. McNab, J.Chem.Res., 1989, (S) 176.

119. H. McNab and I. Stobie, J.Chem.Soc.,Perkin Trans.1, 1982, 1845.

120. e.g. M.F.R.Mulcahy, B.G. Tucker, D.J. Williams, and J.R. Wilmshurst, Aust.J.Chem., 1967, 20, 1155.

121. L.M. Harwood, Aldrichimica Acta, 1985, 18, 25.

122. A.I. Vogel, 'Textbook of Practical Organic Chemistry', Longmans, London, 1978, p.269.

123. C.F.H. Allen and J. Van Allen, Org.Synth., 1955, Coll.Vol.III, 765.

124. T. Kamiya and T. Teraji, U.S., 4 350 692, (1976); (Chem.Abstr., 1983, 98, 7180d).

125. G. Cohn, J.Prakt.Chem., 1900, 61, 550.

126. A. Padwa, P.H.J. Carlsen, and A. Ku, J.Am.Chem. Soc., 1978, 100, 3494.

127. F. Mayer, Ber.Deut.Chem.Ges., 1909, 42, 1132.

128. NENCKI, Chem.Fabr.v HEYDEN, D.R.P. 46756; Frdl, 2, 137; (Beil., 10, 80).

129. N.G. Gaylord and P.M. Kamath, Org.Synth., 1952, 32, 25-6.

130. Chem.Fabr. v HEYDEN, D.R.P., 70519, Frdl, 3, 833; (Beil., 10, 78).

131. A. Einhorn and H. Pfeiffer, Ber.Deut.Chem.Ges., 1901, 34, 2953.

132. M.R. Diaz-Mondejar and M.A. Miranda, Tetrahedron, 1982, 38, 1523.

133. O. Weber, Ber.Deut.Chem.Ges., 1892, 25, 1743.

134. A. Luttringhaus and K. Hauschild, Chem.Ber., 1940, 73, 145.

135. Reference 87, p.228.

136. H. Gillman and A.L. Jacoby, J.Org.Chem., 1939, 3, 108.

137. H. Gillmann and G.R. Wilder, J.Org.Chem., 1957, 22, 523.

138. S. Gronowitz, M. Herslof, R. Svenson, G. Bondesson, O. Magnusson, and N.E. Stjernstrom, Acta Pharm. Suec., 1978, 15, 337.

139. S. Oae, K. Iida, K. Shinhama, and T. Takata, Bull.Chem.Soc.Jpn., 1981, 54, 2374.

140. Reference 87, p.251.

141. 'Dictionary of Organic Compounds', 4th Edition, Eyre and Spottiswoode, London, 1965, Vol.2, p.751.

142. S. Trippett, J.Chem.Soc., 1957, 419.

143. C.G. Choudry, G. Sundström, F.M.W.v.d. Wielen, and O. Hutzinger, Chemosphere, 1977, 6, 327.

144. R.P. Staiger and E.B. Miller, J.Org.Chem., 1959, 24, 1214.

145. M.J.S. Dewar and D.S. Urch, J.Chem.Soc., 1957, 345.

146. E.M. Ruban and M. Kornilov, Zh.Org.Khim., 1973, 9, 2582.

147. R.A. Abramovitch, M.N. Inbasekaran, S. Kato, T.A. Radzikowska, and P. Tomasik, J.Org.Chem., 1983, 48, 690.

148. R. Sabatier and P. Mailhe, Compt.rend., 1912, 155, 260.

149. K. Bedall and O. Fischer, Ber.Deut.Chem.Ges., 1881, 14, 1366.

150. J.V. Braun, H. Gruber, and G. Kirschbaum, Ber.Deut.Chem.Ges., 1922, 55, 3668.

151. D.J. Cremin and A.F. Hegarty, Tetrahedron, 1977, 33, 1823.

152. C. Liebermann and St.V. Kostanecki, Ber.Deut. Chem.Ges., 1884, 17, 131.

153. Reference 122, p.684.

154. E. Bamberger, Chem.Ber., 1903, 36, 2042.

155. B.D. Tiffany, J.Am.Chem.Soc., 1948, 70, 592.

156. Reference 141, Vol.5, p.2882.

157. O.H. Wheeler and H.N. Batlle de Pabon, J.Org. Chem., 1965, 30, 1473.

158. O. Isler, H. Gutmann, M. Montavon, R. Rüegg, G. Ryser, and P. Zeller, Helv.Chim.Acta, 1957, 40, 1242.

159. H.O. House and G.H. Rasmusson, J.Org.Chem., 1961, 26, 4278.

160. A. Hercouet and M. LeCorre, Tetrahedron, 1981, 37, 2867.

161. Reference 141, p.343.